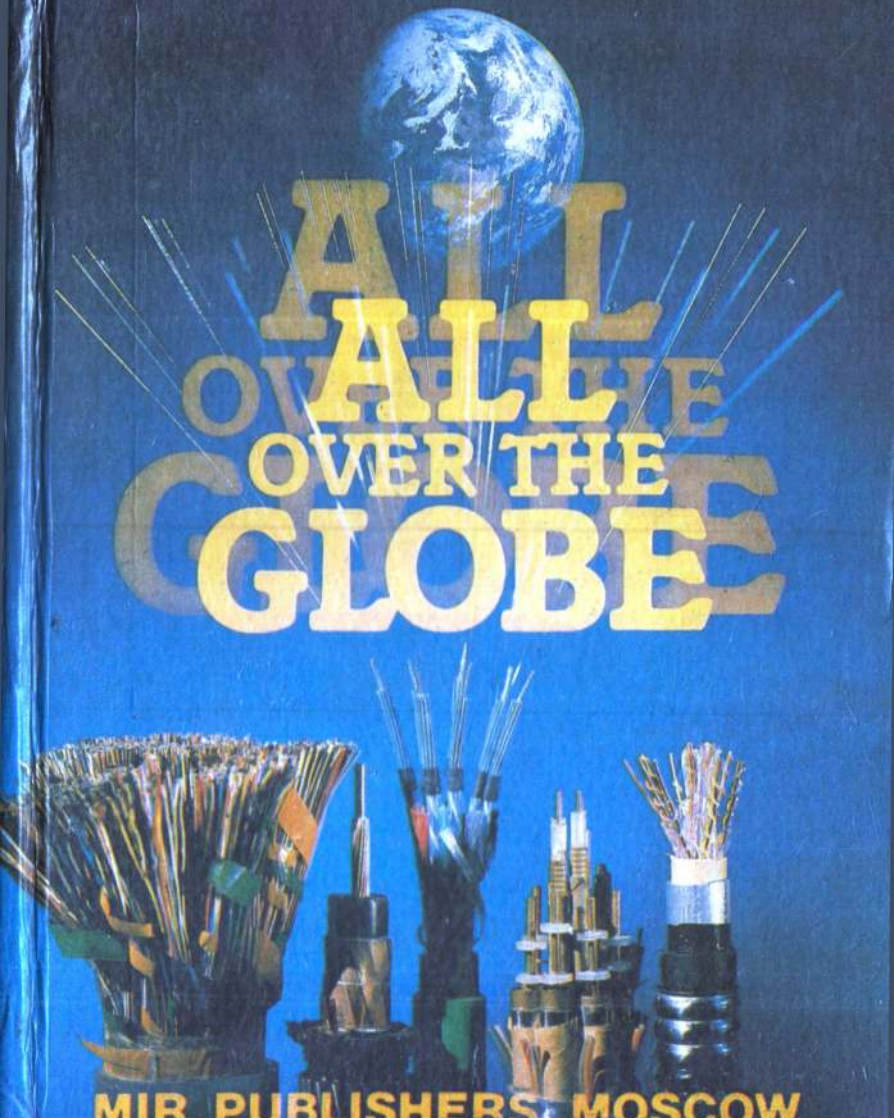
D. SHARLE

ALL OVER THE GLOBE



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David L. Sharle, Candidate of Technical Sciences and Senior Research Worker, has penned 180 publications, including 25 books on the history, theory, design, engineering and manufacture of communication cables. "All Over the Globe" has brought him a 'Society for Knowledge' award.

* HOW MAN FARED IN THE PRE-CABLE AGE

* THAT THE WORLD'S FIRST ELECTRIC COMMUNICATION LINE WAS BUILT BY A SPANISH PHYSICIAN

* WHY EARLY UNDERGROUND CABLE FAILED

* WHY IT WOULD HAVE BEEN IMPORTANT FOR A FRENCH FISHERMAN TO KNOW THAT 'ALL IS NOT GOLD THAT GLITTERS'

* HOW MANY CONVERSATIONS CAN BE TRANSMITTED OVER A PAIR OF CONDUCTORS AND OVER A CABLE

* WHAT THE COUNTER-ARMOUR IS LIKE AND WHY IT IS NEEDED

* WHICH FIBRE IS SLATED TO RIDE HIGH IN THE 21ST CENTURY AND WHY AND ALSO HOW ACCIDENTS, CHANGE AND LUCK HAVE LED TO DISCOVERIES AND INVENTIONS

– ALL OF THIS AND EVEN MORE YOU'LL HAVE LEARNED ON READING THIS BOOK FROM COVER TO COVER

From a painting by Christian Sell showing the installation of a telegraph cable between Berlin and Cologne in 1879 (inside front cover)

ALL OVER THE GLOBE

Д. Л. Шарле

ПО ВСЕМУ ЗЕМНОМУ ШАРУ

Прошлое, настоящее и будущее кабелей связи

Москва
«Радио̀ и связь»

D. SHARLE

ALL OVER THE GLOBE

The Past, Present and Future of Communication Cables

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by
Boris V. Kuznetsov

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About the Book

What you have in front of you is a story of cable, the backbone of many of the communication lines criss-crossing the world today.

Infrequently, we tend to think of cable lines in an unjustly simplified way. But a cable communication link nowadays is a highly sophisticated engineering structure built up of many components among which cables figure very high in terms of materials and money.

Nor has cable been given its due in popular science books. This book is an attempt to fill the gap, at least in part. It covers many types of communication cable: local and long-distance, undersea and transoceanic, voice- and carrier-frequency, wire and optical, and brings out what is most important about each.

Although the story is focused on cable, the author traces its history against the background of the path covered by all of electric communications. He, therefore, wanders off the 'cable trail' sometimes, but he does so in order to look even at well-known things from a new angle, to cite unpublished sources, and to unravel curious facts.

It is not easy to stick any particular tag to the book. For it is a medley of popular science and a detailed historical study into cable communications. This might seem a literary liberty, but I like the author's quest for true and accurate detail, timely recourse to historical documents, and a vivid and easy story-telling. In all of this, he does not sacrifice a single bit of engineering essence.

Another good thing is that the author mentions the names of those who have contributed to the emergence and advance

of cable communications through their theoretical work and inventions.

It may be hoped that this book penned by an enthusiast will give pleasure and be useful to the broad reading public – from young people still planning their future careers to venerable specialists who may find a fact or two they did not know before.

V. I. Siforov,

Corresponding Member of the USSR Academy of Sciences, Chairman of the A. S. Popov Scientific and Technical Society on Radio, Electronics and Communications.

From the Author

Communication cable has played a vital role in the modern history of civilization. Its own history, too, is full of interest, crowded as it is with unexpected and tight turns, sometimes hopeful and sometimes dramatic.

As a Russian proverb goes, "You meet a man by his clothes, but value him by his brains". Well, communication cable is what you might call unattractive by its clothes – dull and bleak. If you cut it, you will see circles – some of them small and the others a bit larger. A primitive uniformity by all standards. There is no room for your imagination to carry you away.

But if, on having read this book, the reader values cable by its 'brains', that is, the brainwork that has gone into making it what it is today, with any one of its conductor pairs capable of carrying conversations between tens, hundreds, thousands or even tens of thousands of people at a time; by the brainwork through which the cable communication lines spanning the globe over land and undersea have come to be the veritable nerves of the organism we call human society; by the brainwork that will make the cable worth of use in the twenty-first century, the author will feel his modest task fulfilled.

The book is too small to tell a story as fully as one might wish, covering all of the original ideas that matured in the first half of the twentieth century, the multitude of disputes, some of them going on for years, and the clashes between cable makers and cable users. As in making the final print of a motion picture, some of the material has had to be cut out.

This book is for the broad reading public, but the author

addresses above all those who are about to take, or have taken, interest in cable communications for all the challenges and appeals this field can offer.

The reader will find in the book simple formulas, tables and drawings bearing on cables – you cannot possibly feel the beauty of science and technology without recourse to the attributes that are used by scientists and engineers. But even the 'hardest' pieces of material are mainly presented at the school level in mathematics, physics and chemistry.

The author will be grateful to all those who will care to send in their remarks, queries, refinements and suggestions on the subject-matter of the book, especially with regard to historical material on cables and communication lines.

Introduction

> "If you limit yourself to a knowledge of the present but neglect the past, you will never understand the present".
>
> *Gottfried Wilhelm Leibnitz*

We are living in the surprising time of nuclear power plants, nuclear-powered ships, space probes, synchrophasotrons, lasers, supersonic airliners, space TV, supercomputers, and smart robots. But the most surprising thing is that man has lost his capacity for surprise. A lunar rover is just as normal as anything. An astronaut stepping down on the Moon is normal, too. There has been a voyage around the planet Venus – so what? There has been a rendezvous with the planet Saturn – that's just a matter of course.

Telecommunication, or exchange of information over distances, is among the most remarkable things that man has accomplished. Actually, there are many forms of telecommunication. These are telephone and telegraph services, radio broadcasting and TV, teletext (transmission of whole pages of printed matter) and facsimile (transmission of still pictures), and, of course, transmission of statistical and other data for processing by computers. And in all of them, there are only two tools of exchange – either wire transmission (mainly, over cable lines) or what appears to be, in a sense, its antipode – wireless or radio transmission, be it via communications satellites, microwave radio links, or through the use of long, medium and short radio waves. It would seem hopeless to set one against the other or to give preference to wire over radio transmission. Both have been serving man dutifully. Nevertheless, the rivalry between the two, started at the turn of the century, has been going on all the time.

Three whales support the present-day telecommunications

network. One has to do with what are technically known as subscriber facilities, such as telephones, TV sets, and telegraph sets. The other refers to switching centres, or exchanges, which provide connection between subscribers and route calls as may be necessary. The third is communication lines which link subscribers to exchanges or one exchange to another in one city, between cities, in one country, or between countries.

Man has always been striving to exchange information over distances as long as possible, preferably unlimited. That is why the names of all forms of communications, including the word 'telecommunication' itself have as its first part the Greek word '*tele*' which means '*far*'. The telegraph sends recorded messages over a distance; the telephone sends conversations over a distance; TV sends pictures over a distance. It is these distances, from tens of metres to tens of thousands of kilometres, that cable lines have been spanning during the past 150 years.

"Statistics knows everything", as the Soviet writers Ilya Ilf and Evgeny Petrov tell us in their classic, "The Twelve Chairs". Or, perhaps, 'almost everything'? For no statistician today would be able to give us the total length of cable communication lines set up on the Earth. Nor would the author. In a round-about way, we can find that the telephone networks in all the cities of the world use an equivalent of two thousand million kilometres of what are called pairs, or two-wire circuits. Early in the twentieth century, it was in vogue to say how many times all the communication lines could have girdled the globe. Today's yardstick appears to be the Solar system itself.

It is near to impossible to tell the global distance spanned, between them, by the cable lines interconnecting cities and those used at mines, factories and other businesses. It is likely that the length of all communication cables throughout the

world is over 100 million kilometres – cables with pairs from one to several thousand, buried in ground or sunk in water, strung overhead or installed in buildings.

As with human beings, every brainchild of scientists and engineers has a fate of its own. It may be happy or unhappy, easy or full of hardships, just or unjust. The best word for communication cables seems to be 'modest' – not so eye-catching or breath-taking as that of radio, say. Speaking of radio, a good many boys, and not only boys, have built a radio set, at least the simplest one, in their lives. Quite a number of people, especially radio hams, know the call sign of the famous radio operator Ernest Krenkel of the Soviet Union who was among the first to spend many days on drifting ice in the Arctic. All people in the USSR and many guests from abroad hold their breath at the sight of the huge Ostankino TV Tower in Moscow. Many families throughout the world spend their evenings, watching telecasts relayed via outer space. At one time, a popular passtime among schoolboys was to build radio transmitters. Today, they are building scale models of space craft, communication satellites, and orbital solar stations.

But has any one admired communication cables? Hardly so, except for specialists. As a rule, you cannot see a cable – it is hidden from your eyes, and 'stands its watch', I'd say, deep in the ground or water for decades. Even if you happen to see it – when it is being laid, for example, – wound on large, unwieldy wooden drums, what is there about it to admire? Long, flexible, snake-like, as thick as your arm or sometimes greater.

In the company of all designs, kinds, and sorts of telephone instruments, colour TV sets, and radios, cable is just tolerated, but it is deprived of interest or love, like Cinderella in the famous fairy tale by Charles Perrault. Most often, the layman would remember it (and not with a good word, at that)

in two cases. One is when he is waiting for a telephone to be installed in his flat too long because there is no cable available. The other is when a telephone aready installed goes dumb and deaf because of a failure somewhere along the cable line.

Nor has communication cable been lucky in popular science books. Books about the telegraph and the telephone, their invention and progress, run into hundreds or even thousands. Those about cables count just a few dozen. Most popular books on telecommunications mention cables only in passing.

It is therefore instructive to quote B. S. Yakobi, the famous Russian scientist and electrician. Delivering his speech, "On Electric Telegraphy", during a public session at St. Petersburg's Academy of Sciences on December 29, 1843, he said: "...I beg you to leave me a few minutes more so that I could dwell on the most important thing for any telegraph transmission – a current-conducting, galvanic circuit intended to interconnect two distant points – sending and receiving".

The history of cables is directly or indirectly linked with the lives of a number of scientists and engineers, both of world renown and known only to specialists. In as far as it is possible, this book pays tribute to them, too.

Transmission of electric signals over lines between distant points had become a fact of life well before ways and means were devised to transmit electric power. This is not a claim for superiority, but an expression of a logic development. The first step into the unknown is the hardest of all. Yuri Gagarin circled the planet Earth only once and stayed in space 108 minutes, or 1.8 hours. In 1982 and 1984, Soviet cosmonauts stayed in orbit for over 5050 and 5650 hours, respectively. In 1987, Yu. Romanenko stayed in space for 326 days (more than 7800 hours), which is a new record.

Of course, it was easier first to transmit a current of several milliamperes over a circuit, and then to handle amperes,

kiloamperes, or megamperes. The first power transmission line was demonstrated in 1882 when telegraph lines had been a booming activity for some time already.

State-of-the-art communication cables show unique capabilities, but they have had to travel a long and uneasy path. What happened before and along this path is told in this book.

Chapter One

The Age Before Cable, or from Signal Drums to Electricity

MESSENGERS, BELLS, FIRES

It has been in all times, including prehistoric, that man has strived to get and pass on news as fast as he could. At first people communicated with inarticulate sounds, hand movements, and mimics. Gradually there appeared what we know today as speech. But even then a person could tell what he wanted to another at a distance of a few hundred metres at best. This spurred the search for ways and means of extending this distance (the transmission range, as we would say today).

Hand signs first came to be used for message transmission within line-of-sight distances.

In Persia in the sixth century B. C., they built tall towers and put slaves with far-carrying voices atop to shout messages between the towers. As many as thirty messages a day could, it is claimed, be transmitted that way. On battlefields, a 'live telephone' would sometimes be set up of warriors who would pass orders by word of mouth down the line. As Gaius Julius Caesar (102-44 B. C.) confirms in his "Notes about the Gallic War", the Gauls used this manner of message transmission in the first century B. C.

Ancient China used gongs for that purpose. The natives in Africa and America preferred signal drums hollowed from tree trunks, with round or narrow holes cut in them. These drums, some of them up to four metres long, were struck with sticks of 'iron wood'. Working his sticks faster or more slowly, now with all force and now just touching the drum, and passing from one place on the trunk to another, the sender could produce a scale of seven sounds varying in pitch. Putting these sounds together in various ways, the sender could pass on

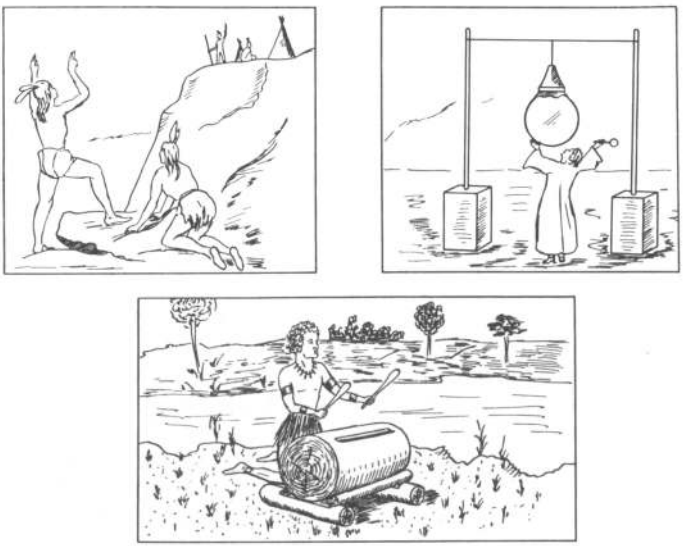

Fig. 1.1. Communication by language of signs, a gong, and a signal drum

messages over appreciable distances and at a fairly high rate. Each tribe used drums of its own design and had what we would call 'duty operators' on a round-the-clock basis. Should a message come from a neighbouring village, the 'operator' would pick up his sticks and pass it on at once. Sound signalling in Africa was in operation for many centuries, with signal drums sometimes made of elephants' tusks. Their sounds were heard by the British traveller David Livingstone (1813-1873) who explored Central and South Africa in the mid-nineteenth century, and by Sir Henry Morton Stanley (1815-1881) who was sent out as an American newsman to find

the lost Livingstone, and later became an African explorer himself.

During the colonial wars at the turn of the century, the Africans used their 'drum telegraph' to exchange messages about the movements of the European troops and other military news at an amazing speed, covering a distance of 300 km a day, and the African war leaders could use them to advantage.

Sound signals were also produced by horns, trumpets, bells and, after gun powder had been invented, by shots from rifles or cannon.

In ancient Moscow, bells were used not only when a fire had broken out, but also to indicate where the mishap had occurred. The fire order of that time instructed: "Should a fire break out in the Kremlin, strike three alarm bells at full swing and a high rate. Should a fire break out in Earthtown, strike the alarm bell at Privy Tower at half-swing". The belfries set up on the hills of the huge Russian expanse used to send out messages of appeal, joy, or sorrow from village to village over distances running into tens of kilometres.

As human society plodded ahead, sound signalling gradually gave way to a better technique – signalling by light. Light travels at a speed which is a million times faster than that of sound. As measured at zero degrees Celcius and normal atmospheric pressure, sound travels through air at 331 metres per second, while light does so at about 300 thousand kilometres per second. During a distant thunderstorm, we would first see a lightning, and then hear the rumble of a thunder – light reaches us well ahead of sound. No less important is the fact that we can see light from a far greater distance than we can hear sound: a light beam reflected from a pocket mirror can be seen at a distance of twenty-five or thirty kilometres.

The first to be used for light signalling were camp fires. As

the legends three thousand years old go, camp fires stood in good stead at least twice during the last night of the Trojan War which the ancient Greeks fought against Troy*. That was in the thirteenth century B.C. The great Latin poet Virgil (70-19 B.C.) tells us in his "AEneid" that the Greeks following Odysseus's counsel built a huge wooden horse, dismantled their camp and went out to sea as if lifting the siege and going home. In the meantime, they sent an alleged defector, Sinon, who beguiled the Trojans and persuaded them to admit the Wooden Horse into the city, helped the Greeks hidden in the Horse to get out, and made up a large camp fire at the city gates broken up by the Horse party. This was a sign for the Greeks lying in ambush not far away that the way into the city was open.

Another legend told by AEschylus (525-456 B.C.), the father of the Greek tragedy, in his "Agamemnon" sounds more forceful from the viewpoint of communications history. King Agamemnon who led the Greek troops in the Trojan War told his wife Clytemnestra he would let her know at once when Troy had fallen and the blood-shedding war was over. To make his plan work, the king sent out his servants who were to make up signal fires at the tops of the mountains on the islands between Asia Minor and Greece. There were a total of eight signalling posts (we would call them repeaters today), spanning between them a total distance of 550 kilometres from Mount Idae near Troy to Mount Arakhneipe not far away from the Castle of Mycenae. The slave posted on the roof of the castle every night saw a bright fire at the top of the far-away mountain one morning. In this way, Clytemnestra was the first to learn that the great Troy had fallen.

The legend has a tragic end. When the triumphant Aga-

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* Troy, or Troas, was an ancient city in Asia Minor. Its site is occupied by the Turkish town of Kutkaleh today.

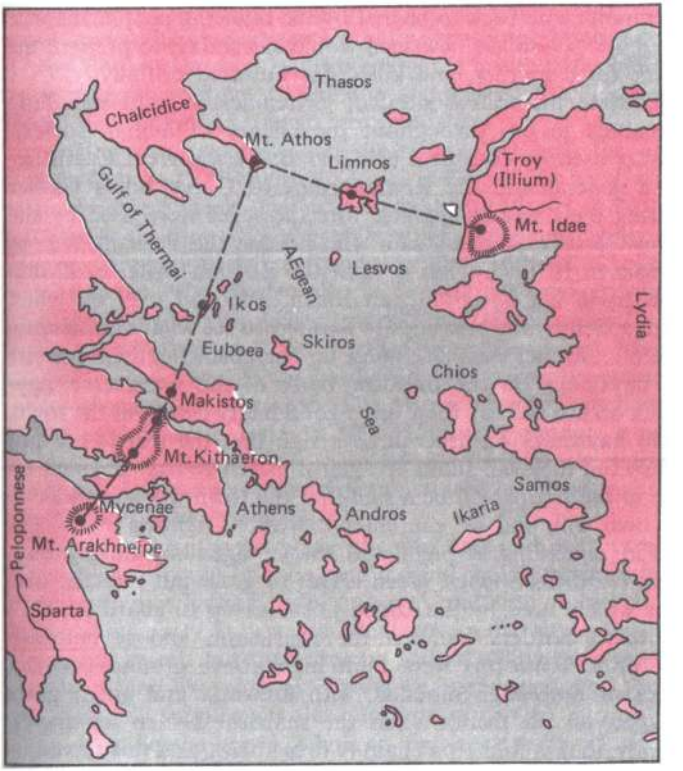


Fig. 1.2. Line relaying fire signals about the fall of Troy (the fifth century B. C.)

memnon came back to be met by the rejoicing people, his wife used her 'scoop' (as newsmen would say today) to prepare the scene for a murder, and killed her husband brutally.

Despite the wicked deed of Clytemnestra, light signalling remained in use throughout the history of human society. It was used by Hannibal (247-183 B. C.), the great Carthaginian general and the Roman emperor Gaius Julius Caesar during their war campaigns. Fire messages were used by the Don Cossack Stepan Razin who headed the Peasant War in Russia in 1670-71. That is what the Russian writer S. Zlobin tells us in his novel "Stepan Razin": "Now I tell you what, Mitya. Send your best boys to Saratov to see what's happening there.... Rather than ride home on horseback, let them put fire to haystacks on the meadow bank of the river. One haystack on fire will say there are a good many troops in the town. Two haystacks on fire will be a sign that the troops are not many but they will stand up against us. Three haystacks set on fire in the steppe will be a sign that the town will surrender of its own will, and we can enter it without fighting".

Fire signalling at night and smoke signalling during daylight (with fresh twigs, green leaves or grass put into the fire) was widely used by the armed posts set up to guard Russia's southern borders between the fourteenth and seventeenth centuries. Platforms were built high above ground between trees or atop high mounds, with firewood and green grass heaped up on them. When the sentries saw an advancing enemy, they would set a chain of fires ablaze, and this served as a warning to their countrymen. It would take two hours and a half at most for a 'fire message' to travel the distance from Russia's southernmost point to its capital, Kiev.

The history of fire signalling would have been incomplete without a mention of its use by the Indians who lived on the archipelago separated by the Strait of Magellan from the

southernmost extremity of South America. They, too, used camp fires at their guard posts, and this prompted James Cook (1728-1779), the famous English navigator in the latter half of the eighteenth century, to call the archipelago the "Land of Fires" (or "Tierra del Fuego" in Spanish).

An interesting example of light signalling opens the first chapter in a book, "Where No Voice is Heard", by the Czech writer Ludvic Souček. The action of the story is set in North America at the time when the white settlers were colonizing the country. A party of white troops on horses moves across a plateau in the Wild West, while the Indians are keeping watch on their advance. Using cheap mirrors to reflect sunlight, the Indians send messages to other tribes for reinforcement. Many warriors speed towards the battlefield, and defeat the whites.

Souček dates his narrative, "The Mirror Shards That Killed a Division", back to June 25, 1876. Curiously enough, it was the day when Alexander Graham Bell on the opposite side of the North American continent demonstrated his invention, the telephone, for the first time.

Fast as it was, the language of camp fires and mirrors was too meagre. It could only be used to send signals agreed upon in advance, mostly 'Yes' or 'No' about something of interest to the receiving party. It was possible to send a warning about an advancing enemy, but there was no way of telling his strength and describing his weapons. Therefore, messengers had to be sent along to supplement the information carried by fires.

When on September 13, 490 B. C. the Greek army defending their country and liberty under the joint command of ten strategi headed by Miltiades of Athens defeated the Persians under King Darius in a battle on a plain near the village of Marathon, a runner was sent to Athens to report the victory. A runner, a young Greek warrior whose name was Eukiphilippides, covered, as the legend goes, the 42 kilometres and

	1	2	3	4	5
1	A	B	Γ	Δ	E
2	Z	H	Θ	I	K
3	Λ	M	N	Ξ	O
4	Π	P	Σ	T	Υ
5	Φ	X	Ψ	Ω	

Fig. 1.3. The telegraph code used by Kleoxenes and Demokleitos

195 metres* between Marathon and Athens non-stop, shouted "Rejoice, we've won!" at the city gates, and fell dead.

In the fifth century B.C. Kleoxenes and Demokleitos, two Greeks of Alexandria, came up with an invention which was truly outstanding for their time. They proposed to transmit messages over distances using combinations of two torches for the letters of the Greek alphabet. They wrote the 24 Greek letters in a square table which had five rows and five columns, so that each square except the last one had one letter. Each transmitting station consisted of two walls each with six castellations separated by five spaces. The torches inserted between the castellations on one wall gave the row, and the

*This is however a popular misconception. Actually the distance from Marathon to Athens is thirty seven and a half kilometres, and the Greek messenger had run it in less than three hours. Today's Marathon race follows the rule established at the 4th Olympic games held in London in 1908. Its 'Marathon' runners were to cover the distance from the Windsor Castle to the Olympic Stadium, which is 42 kilometres 192 metres.

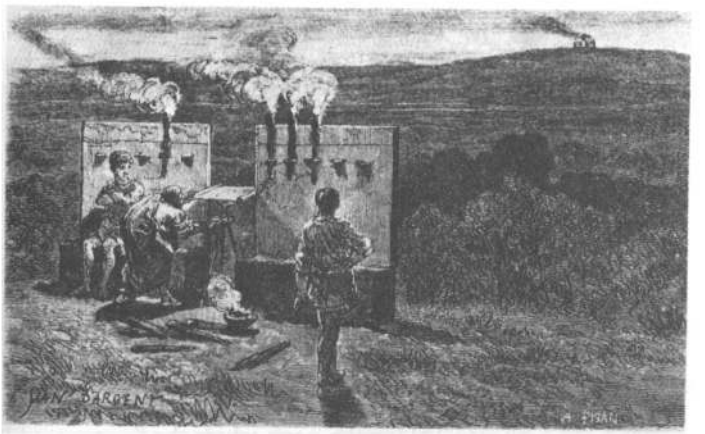


Fig. 1.4. Message transmission by means of 'communication walls'

torches between the castellations on the other wall identified the column; their intersection gave the letter transmitted.

The combination of torches shown in Figure 1.4 identifies the letter in the first row of the third column, that is the Greek 'Γ'. That was probably the first telegraph code in history. With it, it was possible to transmit any messages, not agreed upon in advance, as a string of separate letters. Unfortunately, because they were bulky and could operate only at night, and then if the weather was good, the 'communication walls' described by Polibies in the second century B. C. did not find practical use. Still, they may be viewed as the forerunners of what we know as the telegraph today. In any case, the name 'torch telegraph' seems to be quite deserved.

The first eighteen centuries of our times added little to what we have described by way of communication. One of these additions was perhaps the horse mail or relay service organi-

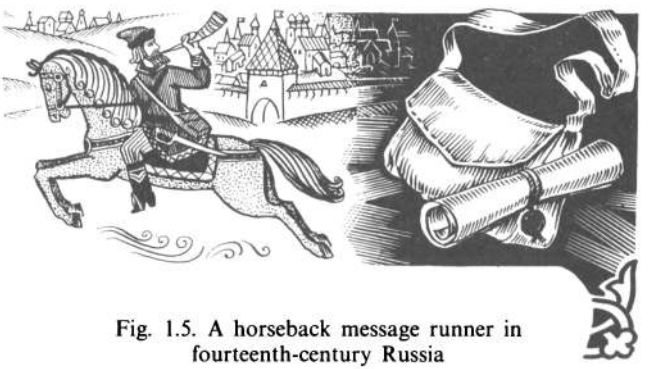


Fig. 1.5. A horseback message runner in fourteenth-century Russia

zed in some countries already in the fourteenth century. Stations were set up all along the route where the drivers could change horses. The speed of travel was as high as 150 or even 200 kilometres a day. Marco Polo (1254-1324), a famous traveller born in Venice, even quoted 400 kilometres a day which works out to an average speed of 16.5 kilometres an hour. In 1625, when he was coming back from Duke of Buckingham with the necklace for Anne of Austria, d'Artagnan, the romantic hero of A. Dumas' "The Three Musketeers", rode at full speed from St. Valery, south-west of the port of Calais, to Paris. On changing his horses at relay stations three times, he was able to cover close on 255 kilometres in twelve hours. His average speed was thus 21 kilometres an hour.

It is interesting to note that the Russian Field Marshal Suvorov had, during his 1768-1799 campaigns, no swifter means of sending orders to his troops than Alexander the Great of Macedonia, the Roman Emperor Caesar, or the Carthagenian general Hannibal.

In 1801, Russia had over thirty-two hundred relay stations and over thirty-seven thousand horses to serve them.

THE ARMED TOWERS

The topmost rung on the ladder of pre-electric communications belongs to the semaphore telegraph. Credit for its invention goes to a brilliant French engineer, Claude Chappe (1763-1805), although the idea of the 'visual telegraph' was put forward before him by the prominent English natural philosopher Robert Hooke (1635-1703), who deduced what we know as Hooke's law describing the elasticity of solid bodies. In a discourse to the Royal Society in London he proposed to post large letters on high scaffolds and to read them from a distance with a viewing tube which had been invented by that time. Hooke's idea was however used on a limited scale. An attempt was made in France in the 1690s to attach the letters of the alphabet to the slowly rotating sails of a windmill, but the attempt brought no fruit. A century later, in 1790, Claude Chappe and his brothers set about to devise their semaphore. They had experimented for three years before they were able, in the summer of 1793, to show their invention to a commission appointed by the National Convention of the French Republic. That was a demonstration semaphore line 6.5 kilometres long, with two stations at its ends and one intermediate station between them. A year later they built and put in service the world's first operational line of telegraph stations between Paris and Lille. It was two hundred and thirty kilometres long and had twenty-two stations. On August 15, 1794, they transmitted in a matter of a half to one hour the first message telling that the Republic's troops had retaken Le Quesnoy. A fortnight later, on August 30, the semaphore carried to Paris another piece of good news about the recapture of Condé.

What was a semaphore station like? Topping the roof of a tower was a metal rod, and pivoted to this was a horizontal longbeam three or four metres long. This looked not unlike the

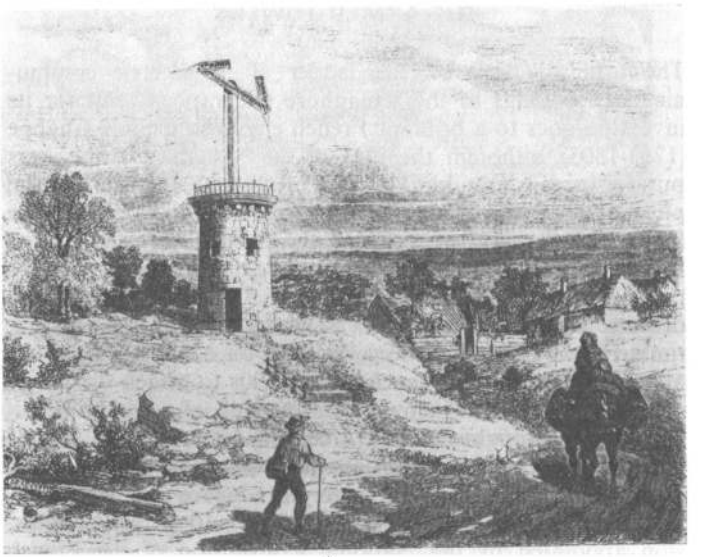


Fig. 1.6. The semaphore station

home TV antenna of our times, except that the longbeam carried at its ends short arms over a metre long, also movable on their pivots. The longbeam and the arms were coupled, as shown in Figure 1.7, by ropes to a winch installed in the room below, occupied by an operator. The longbeam and the arms could be swung into various angles so that a large number of possible configurations could be achieved. The longbeam and the arms were painted black and could readily be seen against the sky at daylight (provided there was no fog to obscure them). At night, burning lanterns could be attached to them, but night transmissions were soon dropped because too many errors would creep into the messages.

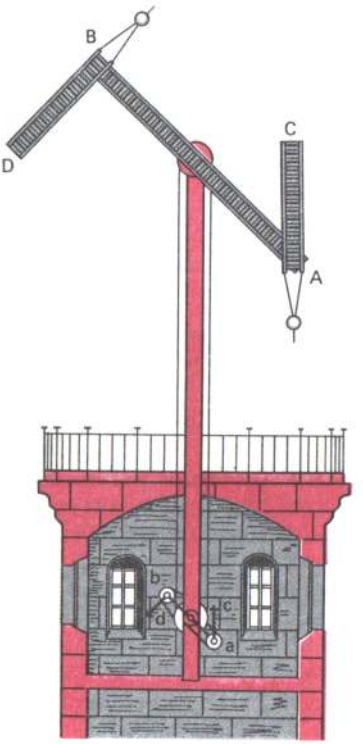


Fig. 1.7. The linkage system used to position the arms atop a semaphore tower

The towers of a line were spaced eight to twelve kilometres apart. Before a message could be transmitted, it had to be coded, that is, written as an array of longbeam and arm configurations. This job was done by an encoder. Thus coded, the message was then passed on to the winchman who

manipulated the longbeam and the arms as requested by the coded array. The winchmen at all succeeding stations simply repeated this code combination. Actually, two men were always on duty at every station: an observer with a spying glass and a winchman. At the last, terminal, station, the received message was put down in writing, decoded, and turned over to the addressee.

The longbeam could be swung into four positions: horizontal, vertical, tilted to the right, or tilted to the left at an angle of forty-five degrees. Each arm, at the left- and right-hand end of the longbeam, could take up eight positions differing by forty-five degrees, thus making an angle of 0, 45, 90, 135 degrees and so on with the longbeam. The result could be a total of $4 \times 8 \times 8 = 256$ configurations, but Chappe picked ninety-two that were most distinct. Arranged into pairs, they were enough to transmit the 8464 most commonly used words Chappe had selected. The words were written into a book on ninety-two numbered pages, each carrying ninety-two numbered words. The first signal of a pair identified the page, and the second, the word on that page.

In his fundamental work on the visual telegraph, the Soviet historian D. Karguin compares three methods of message transmission. In one, messages were transmitted as sentences agreed upon in advance (recall the fire signalling used by Agamemnon, Stepan Razin and ancient border guards). In another, messages were transmitted as strings of letters – a time- and effort-consuming job, but easily intercepted by the enemy. In the third, messages were transmitted as arrays of numbers, each code combination representing phrases, words or, if and when necessary, syllables and letters. This latter method was the fastest of all and – importantly – assured security of communication, a vital consideration for France of the Napoleonic wars. It is a historical fact that Napoleon gave full credit to Chappe's invention and widely used it to circulate

Fig. 1.8. One form of Chappe's telegraph code

orders to his generals. True, to believe Alexandre Dumas the Elder, the numerical code was not one hundred-percent crook-proof. Count Monte Cristo paid twenty-five thousand francs to a signalman at an intermediate telegraph station, telling him to send a false message. The outcome was the loss of one million francs suffered by Danglar, the Count's worst

enemy. Indeed, one of the chapters in A. Dumas' famous novel "Count Monte Cristo" is entitled "The Telegraph". Curiously, except for its title, the chapter has nothing to do with the telegraph at all, but it is dealt with at length in the next chapter bearing some irrelevant title.

One form of Chappe's telegraph code shown in Figure 1.8 is described in some books. As is seen, each letter is shown twice, upper case and lower case. This was hardly needed in transmitting telegraph messages, and the less so by a time- and effort-consuming method. Nor does the telegraph alphabet include the letters X and x, Y and y, and d. Also, it does not seem reasonable to use commas, colons, semi-colons, parentheses and other punctuation marks in a telegraph message.

History is a science of detail. Historically, it is vitally important to know who was the first to advance an idea, who turned it into a fact of life, and who named it. Chappe's invention was first called 'telegraph' in 1793 by one of his assistants. Some sources insist that it was Myotte, a French officer; others argue that it was Claude's brother, Ignace. From French it has found its way into other languages.

In 1795, I. Kulibin (1735-1818), a talented Russian self-made mechanician, working independently of Chappe, proposed his own version of the telegraph. He called it 'the remote informing machine' which was to use both an alphabetic and a syllable code. Unfortunately, Kulibin's idea shared the fate of many of his other inventions. Government officials shrugged it off, and the Kulibin telegraph was tucked away in the Museum of Antiquities.

Many countries followed France's suit in adopting the semaphore telegraph. Sweden did so in 1795 and Denmark in 1802, to be followed by Italy, Spain, Algeria, and Egypt. In 1796, England built its own version of the visual telegraph as proposed by Lord George Murray (1761-1803), although it was obviously inferior to Chappe's. In 1802, a semaphore line

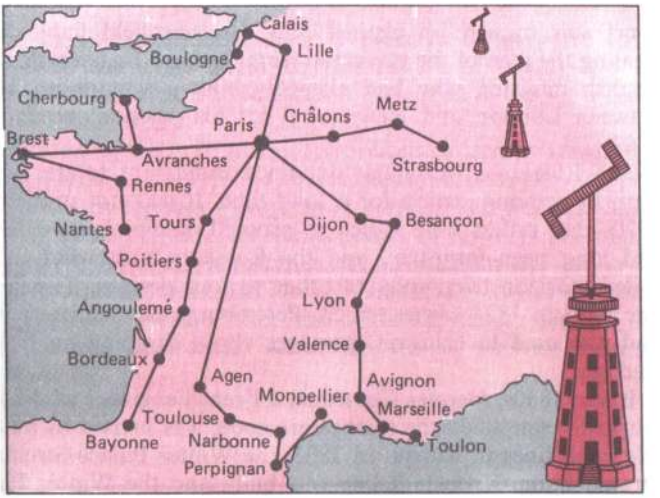


Fig. 1.9. Network of Chappe's semaphore telegraph lines in France in the early nineteenth century

was built between Calcutta and Chenor in India, and a governmental Berlin-Potsdam-Magdeburg-Cologne line was built in Germany in 1832-1834. It ran for a distance of 750 kilometres and had sixty-one stations. In the United States, the first 104-kilometre semaphore line was set up between Boston and Martha's Vineyard Island in 1800.

By 1852, France was covered by a network of 550 semaphore stations stretching over a total distance of 4800 kilometres and linking Paris to twenty-eight most important cities throughout the country. The longest of them was the Paris-Lyon-Marseilles-Tulon line spanning a distance of over a thousand kilometres and having a hundred stations.

A tragic fate fell onto the semaphore's inventor himself. In 1805, Claude Chappe took his own life, broken down by the

court suit framed up against him. He was held liable for stealing the idea of the invention from Richard Edgeworth, an English minister, who had allegedly built a semaphore line between London and Newmarket for his personal needs in 1767.

The Russian government remained indifferent to the new form of communication for a long time. It was not until the 1820s that orders were issued to proceed. Kulibin's invention had long been forgotten, and the Russians built what they called 'horizon telegraphs' of other various designs. The first line built in 1824 connected St. Petersburg and Schlisselburg and was used to transmit messages about shipping on Lake Ladoga.

In the 1830s, Jacques Chateaux, a French engineer who had markedly simplified the semaphore code, was invited to build telegraph lines in Russia. In 1833, the Winter Palace-Strelna-Oranienbaum-Kronstadt line was built, and the Winter Palace-Tsar Village-Gatchina line in 1835. During the years 1835-1838, the world's longest semaphore line from St. Petersburg to Warsaw was built. One more year was spent to test it, and it was formally opened for round-the-clock operation on December 20, 1839. This 1200-kilometre line had 149 standard towers each over twenty-one and a half metres tall, topped by metal rods three metres long, and was run by a staff of nineteen hundred and eight.

The Popov Communications Museum in the USSR has a file in its archives. The file bears a curious title: "On the Payment of 120 000 roubles to the Foreigner Chateaux for Concession of His Telegraph Secret to Russia". We would call it a licence today.

The semaphore remained in service in Russia until 1854.

A semaphore line took from two to fifteen minutes to transmit one signal, depending on the number of intermediate, or relay, stations it had and the prevailing weather. Over lines

1000 to 1200 kilometres long, a message of forty-five to a hundred characters could be transmitted in twenty-two to thirty-five minutes. The semaphore remained in use for a total of over sixty years.

Because of the inevitable interruptions caused by rains, fog, or blizzards, it could fill the communication needs only in part. Advances in economy, progress in cultural and political links among countries, and the construction of railways prompted the search for a faster communication medium less prone to chances. Indeed, work had already been under way in scientific laboratories since the latter half of the eighteenth century on what would later come to be known as electric communication.

Chapter Two

Of Those Who Have Laid the Foundation

A FEW FACTS ABOUT ELECTRICITY

Still it was Thales! Early observations of magnetic and electric phenomena are linked with the name of the Greek philosopher Thales (625-547 B. C.) who lived in the town of Miletus on the Mediterranean coast. There was a good deal of reason for his contemporaries to look at Thales as one of Greece's seven sages. He was a philosopher of the physical school and the father of ancient philosophy in general as the head of what we know as the Miletian school of philosophy. Among other things, Thales liked to show his disciples an intriguing experiment. He took a hank of wool and rubbed it against a piece of amber. As he did so, the spectators could hear a faint crackling sound as they stood quietly around. Then he moved the amber slowly towards a heap of wood shavings, straws, or flax threads. With the amber still within a few centimetres of the heap, the small objects jumped into the air and were attracted by the amber. The Greek name for amber is electron. That is how static electricity was discovered in the sixth century B. C.

There is a body of opinion that it was not Thales but his young daughter who had discovered the thing when she rubbed a piece of amber against fur. Quite likely, for both amber and fur would be of more interest to a young lady than to a venerable scholar. Indeed, chances are that the intriguing property of amber was known well before Thales. Women in ancient Greece used spindles made of or decorated with amber. As woolen yarn rubbed against the spindle, the amber first attracted and then repelled the fine lint from the yarn. In a way, spinning was accompanied by a spontaneous and amu-

sing play. Still, it was Thales who tried to get insight into the thing for the first time and to explain why a rubbed piece of amber would show this short-lived property of artificially induced attraction. He saw something common between this property of amber and the ability of a lump of magnetic ore to attract iron filings. And, again, he was the first to describe both phenomena.

Quite a number of discoveries, both big and small, have been attributed to chance. This looks and sounds highly entertaining, impressive or, sometimes, dramatic as far as it goes. Unfortunately, this does not go too far. For a discovery usually happens when a chance crowns a chain of regular patterns, the effort of a purposeful search, and a lot of self-denying and often demanding work. Aristotle (385-322 B.C.) was right when he said: "Chance helps an enlightened mind". We will go back to this interplay of the chance and the regular more than once in the succeeding chapters. As to static electricity, man did not take interest in it until twenty-two centuries later.

The Queen's personal physician as the father of magnetism. A contemporary of Shakespeare and Galileo, William Gilbert (1540-1603), personal physician to Queen Elizabeth I of England, was highly industrious in his search of remedies for diseases. For this purpose, he had spent many years reading Medieval Arabic, ancient Greek and Roman manuscripts. In one of them, he read about the mysterious behaviour of loadstone, a magnetic ore. After he had failed to find the plausible explanation of the phenomenon, Gilbert started a long series of experiments of his own. In the twenty years or so that he was busy with loadstone, he described over 600 experiments and discovered the hitherto unknown properties of magnets. All this led him to an understanding of Earth's magnetism. As he believed, all of the planet Earth was a giant magnet, and the globe's poles were the poles of that magnet.

Fig. 2.1. The title page of W. Gilbert's book

To what he had read about Thales's experiments with amber, Gilbert added his own discovery that diamond, sapphire, ruby, opal, amethyst, rock crystal, glass, porcelain, sulphur, and sealing wax could also, when rubbed, attract light bodies, such

as straws, although to a lesser degree than amber. In 1600, he published his fundamental work on magnets, magnetic bodies, and the largest magnet of all – the Earth.

Undoubtedly, Gilbert did great services to science. The scientific community is unanimous in looking upon him as the father of the science of magnetism and electricity. Quite logically, Gilbert was the first to use the term 'electricity' when he said that electric bodies are those which attract in the same way as amber does. His name has been given to the unit of magnetomotive force, the gilbert (Gb), in the CGS (centimetre-gramme-second) system of units.

The ever first source of electricity. Gilbert's study of electricity was carried on a half-century later by the German physicist Otto von Goericke (1602-1686), Mayor of the city of Magdeburg. Called 'the German Galileo' by his contemporaries, he went into the history of science when, in 1654, he made an experiment to prove the existence of atmospheric pressure, using what have since then been known as the Magdeburg hemispheres. Somewhere in the 1650s, he built the forerunner of an electrostatic generator (sometimes called the static machine). It was essentially a molten sulphur ball the size of a child's head, put on an iron shaft with a crank. As he tried many materials with which to rub, that is to electrify, the ball, Goericke discovered quite unexpectedly that the best way to do that was with his own palms. That was a chance discovery again, but it came out of a chain of purposeful efforts. Goericke was also the first to notice electric repulsion: a bit of fluff attracted by the electrified sulphur ball would be pushed away some time later. With the sulphur ball removed from its support and held in his palm, the experimentor could move around the room and cause the fluff to travel where he wanted it to go. Another important discovery made by Goericke was that the electricity produced by an electrified sulphur ball could propagate down a linen thread attached at its upper end

Fig. 2.2. Von Goericke's experiment with a fluff

to the ball for a distance of an elbow (about two feet). As a result, the distant end of the thread was able to attract bits of fluff, small straws, and thin leaves of gold, silver and paper placed about an inch away. This and other of his experiments he described in a book published in 1672 under the title "The New Magdeburg Experiments".

Goericke made his ball by pouring molten sulphur into a spherical glass vessel – after the sulphur had solidified, he broke up the vessel. If he hadn't done that! For in 1709, Francis Hawksby (1666-1713), Fellow of the London Royal Society, built an improved electrostatic machine which used a glass sphere instead of a sulphur ball. Goericke had not lived to see this happen. Is it not an example of a chance that did not materialize? It may well be called an anti-chance. The history of science and engineering is full of them. Yet, although an anti-chance can sometimes retard progress (for as much as a half-century as in Goericke's case), it cannot stop it for ever.

After many experiments, Hawksby found that static electricity could conveniently be produced by rubbing a glass rod – a trick still used at school even now. This had made

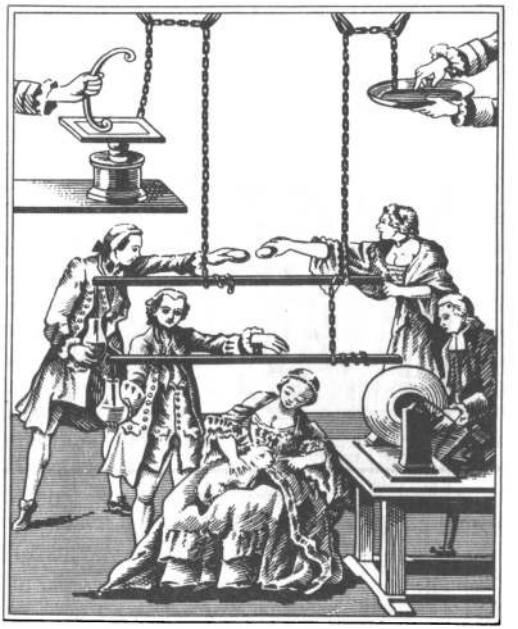


Fig. 2.3. Generation and storage of electric charges from an electrostatic machine in the first quarter of the eighteenth century

experiments with electricity inexpensive and within the reach of everyone.

Electricity runs down a hemp thread. Although it may seem opposite to common sense, the early experiments did not use conductors to transmit electric charge over a distance. In fact, scholars knew nothing about conductors and non-conductors when in May 1730 Stephen Gray (1670-1736), Fellow of the London Royal Society, showed how static electricity could propagate over a distance of eight metres along a hemp thread.

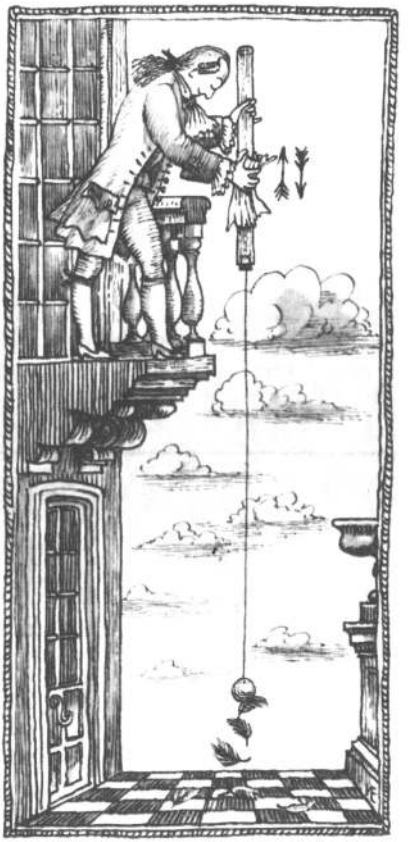


Fig. 2.4. Gray's experiments with the transmission of static electricity over a distance

The hemp thread with a bone ball at its free end emerged from a glass tube about a yard long and an inch in diameter, held by Gray as he stood on the balcony of his house. Each time Gray rubbed the glass tube with a silk kerchief, using his free hand, the electric charge would run down the rope, and the bone ball would attract light objects, such as a thin leaf of brass.

A few days later, the experiment was repeated. Now Gray used a hemp thread several dozen yards long, suspended from loops of silk. Although he was able to show that the 'electric something' could be transmitted for a distance of about three hundred yards over a thread, still hemp is a poor conductor. In all probability, when used in Gray's experiments, it was rubbed with soap or simply moistened.

It was not long before Gray found that a fine copper wire could likewise conduct electricity. He was the first to propose that all bodies should be divided into two broad classes according to how they conduct electricity. The materials that Gilbert called 'electric bodies', such as amber, glass, gem stones, sulphur and porcelain, are poor conductors. Today they are called dielectrics or insulators. Those called 'nonelectric bodies' by Gilbert, above all metals, are good conductors. That was how electric conduction was discovered in 1729.

Incidentally, the terms 'conductor' and 'insulator' were first put in circulation by Jacques Theophil Desaguiller in 1739.

Who invented the amazing jar? In 1746, two reports appeared closely one after the other, describing the same experiment. A glass jar was filled with water, a metal rod was inserted into it through the jar's neck, and an electric charge was conveyed to the rod from an electrostatic machine. The experimentor held the jar in one hand. Each time the contact between the rod and the machine was broken and the experimentor touched the rod with his other hand, an electric spark would jump and cause him pain in the other hand.

One report came from the German priest Ewald Jurgen von

Fig. 2.5. Electrification of a man in the first half of the eighteenth century

Kleist (1700-1748) in Pommern. He wrote that he had discovered the spark in October, 1745. The other report came from the Dutch physicist Peter van Muschenbruck (1692-1761), who was Professor of the Leyden University. He insisted that the jar described by von Kleist had been produced by him, Muschenbruck, at Leyden, earlier, namely in January, 1745. Before long, one more contender turned up. He was a student of Muschenbruck, by the name of Kühneus (or Kahneus), who took part in the professor's experiments. Probably, hard put to name the true inventor, the scientific community, following counsel from Abbot Jean Nollet, a French physicist, named it the Leyden jar after the town of Leyden, where it was first produced. The Leyden jar was the world's first electric condenser.

Electricity from the air. Much was done to unravel the identity of electricity by scientists a decade later, notably by M. Lomonosov (1711-1765) and Georg Wilhelm Richmann (1711-1753), both of Russia, and by the American Benjamin Franklin (1706-1790) who invented the lightning arrester. As early as 1749, Franklin noted there was a good deal of

Fig. 2.6. Muschenbruck's experiment with the Leyden jar

common between 'electric fluid' and the lightning. In the summer of 1750, he proposed an experiment involving a long, pointed iron rod. The rod was to be held high during the passage of thunderstorm clouds so that a spark could be drawn from it. Franklin's idea proved a success in an experiment carried out on May 10, 1752, at Marly, twenty-five kilometres from Paris, France, then in a similar experiment at Bologna, Italy. Finally, Franklin himself made his now famous experiment with a kite on April 12, 1753. On that day, he sent aloft a kite carrying a pointed iron rod during a thunderstorm. A rope was tied to the rod at one end and to a heavy key at the other. The scholar held the rope by a silk ribbon protected against the rain. Franklin's idea was that the kite and the rope would become wet during the rain to provide an easy path for electricity, and plenty of it would flow out of the key, so that a Leyden jar could be charged. The experiment went as planned.

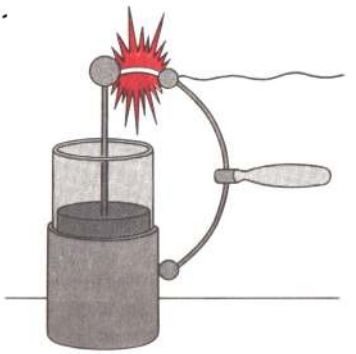


Fig. 2.7. Discharge of the Leyden jar

Blue sparks could be seen jumping between the key and the ball at the tip of the rod inserted in a Leyden jar.

Busy with many things in the field of natural sciences and not only natural sciences, Lomonosov did not experiment with electricity very much. But what he did is enough for him to be ranked among the most outstanding electricians. Lomonosov and Richmann, similarly to Franklin, believed that the lightning was of electric origin. But Lomonosov had arrived at his theory of atmospheric electricity independently of Franklin. That's what he told Richmann when the two had read a report about Franklin's experiment in a journal: "I owe nothing to Mr. Franklin in my theory of electric force in the air".

A year before he had described his observations in a verse:

The spinning ball of glass
Gives off bolts and sparks
Not unlike the flashes
And crackles of a thunderstorm.

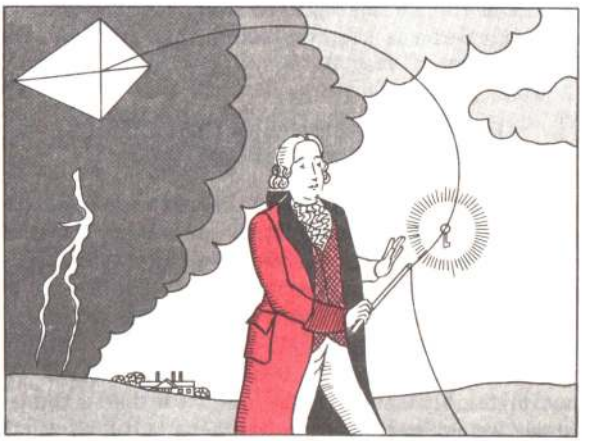


Fig. 2.8. Franklin's experiment with atmospheric electricity

Lomonosov summed up the key points of his theory in a speech, "A Word on the Aerial Phenomena Arising from Electric Force", he delivered at a session of the Russian Academy of Sciences in 1753.

Richmann is more often remembered as the tragic victim of a fire-ball (a globe lightning) which killed him as he watched a thunderstorm. He had studied electrification and electric conduction, discovered electric induction, and invented what he had named the electric indicator – an instrument with which he could compare electric charges in magnitude.

In 1772, G. B. Beccaria (1716-1781), Professor at the University of Torino, noted: "Metals, although they are more pliable (that is, more conductive) than any other bodies, do present a resistance which is proportional to the path travelled by the spark". Thus, he introduced the concept of electric

resistance and applied himself to its study. Among other things he found that water is less conducting than solid metals and mercury.

ELECTRIC COMMUNICATION COMES ON THE STAGE

As we have seen, the electricians of the mid-eighteenth century had got something to go by. That 'something' included the electrostatic machine as a source, albeit weak, of static electricity, the Leyden jar as an electric condenser, and a primitive but sensitive detector or receiver – an electrified body capable of attracting small, light-weight objects. Lastly, they had realized that electricity could be transmitted over a distance, preferably using a metal conductor than a hemp rope.

In short, an engineering basis had been laid for someone to think of electric communication. Indeed, two components of an electric communication system were already available – the transmitter and the receiver. What was lacking was a third component. The point is that information is as a rule produced at one place and used at another, so information and transmission are practically inseparable from each other. Therefore, the third component was to be a medium which would span the distance between the transmitter and the receiver. This medium was to be electric communication lines.

An avalanche of ideas. Stephen Gray, C. Du Fay in the 1730s, L. Lemonnier, Sir William Watson and other scientists in the 1740s proved that electric charges could be transmitted over short distances. Starting in the 1740s, only metal wire was used for the purpose. To insulate it from the ground, the wire was suspended on silk threads, or strung on dry wooden poles or, sometimes, held by a line of people standing on insulating supports (made of resin and wax). Using this sort of insulation, the lines could be from half a kilometre to three kilometres

long. Notably, the line set up by Sir William Watson in 1747 was two miles long.

It is hardly surprising that Johann H. Winkler (1703-1770), Professor of Philology at Leipzig University, should take interest in electricity. Scholars at that time were not so specialized as they are today, and electricity was in vogue. Above all, Winkler is known for his improvement of the electrostatic machine. Instead of a glass sphere, he used a glass tube caused to rotate about its axis by pedals; instead of someone's palms, the tube was rubbed with small leather bags. The bags filled with horse hair were held against the glass tube by springs. As Winkler himself put it, the new machine "offered a possibility to produce strong electric sparks". He described his studies in a book published in Leipzig in 1744 under the title "Thoughts about the Properties, Action and Nature of Electricity, and a Description of Two New Static Machines". Later, somewhere between 1755 and 1766, he replaced the glass tube with a glass disc, and this improved his machine still more.

Winkler was the first to think of transmitting electricity over large distances. He believed that "a suspended, insulated conductor could be used to transmit electricity to the world's end and to make it tangible". This was perhaps the ever first mention of a line as part of an electrical system and the first recognition of its necessity. We may well take his words as the first mention of an insulated conductor, although nothing was said about the materials to be used for the conductor and insulation.

Speaking of transmitting electricity over distances, Winkler stressed that it could "travel faster than the bullet". Today, his comparison sounds naive. Even schoolboys know that the velocity of a bullet is around one kilometre a second. In air, electricity, that is, an electromagnetic wave, propagates at 300 thousand kilometres per second. In a communication cable, an

electromagnetic wave travels a bit more slowly – at around 250 thousand kilometres per second – a thing known to college students. This is a quarter of a million times the velocity of a bullet.

The authors of some books on the history of electricity and, especially, electric communication believe that the idea of transmitting electric signals over a distance by wires was put forward for the first time when a remarkable letter signed by a certain C. M. was published in the *Scots Magazine* on February 1, 1753. Later it was learned that the author's name was Charles Morrison who was a school teacher in the Scottish town of Renfrew. Other sources call him Marshall, though. Briefly he proposed that a "set of wires equal in number to the letters of the alphabet, be extended horizontally between two given places, parallel to one another and each of them about an inch distant from the next to it." Obviously, C. M. had bare, that is uninsulated, wires in mind. The letter went on to explain in detail how the wires were to be connected to the conductor of an electrostatic machine when it was desired to signal a particular letter. On the receiving side, "let a ball be suspended from every wire, and about one sixth to one eighth of an inch below the balls, place the letters of the alphabet marked on bits of paper...". C. M. then proposed to use the electricity from an electrostatic machine, channel it through one of his wires, and let it attract on the receiving side the respective bit of paper with its letter of the alphabet.

That was the ever first concept of the truly electric telegraph, but it never materialized.

Both Winkler and Morrison had quite a number of what might be called 'conceptual' followers – 'conceptual' in two senses. Firstly, because they shared the concept of electric signal transmission over distances. Secondly, because none moved beyond the conceptual stage. Nevertheless, this advance of the telegraph concepts, speculative as they may seem,

paved the way for the practical results that were to come later.

This stream of abstract ideas carried, at last, a few suggestions as to the arrangement of a communication line. On May 30, 1782, the French newspaper "Journal de Paris"carried a letter whose author Simon Linguet, a French lawyer, evolved the following scheme for transmitting electric impulses along "gilded iron wires enclosed in wooden tubes filled with resin and buried in the ground". At the receiving end, there was to be before each pair of wires a foil letter – acted upon by the discharge of a Leyden jar the letter would glow in darkness.

The would-be inventor proposed to use as many pairs of wires and Leyden jars as there were letters in the French alphabet, that is, twenty-four. Indeed, he thought this number could be reduced to five as the Leyden jars could be discharged in various combinations over each pair.

On June 15, 1782, the same newspaper advanced an improvement upon the previous idea: "It would be quite possible to lay a greater number of wires in the same wooden conduit if precautions are taken to insulate them from one another". Unfortunately, the inventor did not even imagine how to go about taking his 'precautions'.

At about the same time, on June 22, 1782, the physicist G. L. Le Sage (1724-1803) of Geneva wrote to a friend of his who lived in Berlin that he, Le Sage, had invented as far back as thirty or thirty-five years before an electric system for 'instantaneous correspondence' in no way more intricate than the one described in May. Eager to prove his involvement in the invention, he described his system in a September number of the same newspaper. An unusual feature about it was that the twenty-four wires were to be laid in a common clay pipe enclosing glazed clay or glass discs spaced 1.8 to 2 metres apart. Each disc was to have twenty-four holes to allow the passage of the wires. In this way, the wires would be held parallel to, and insulated from, one another.

According to another, not confirmed but very plausible version, Le Sage carried out in 1774 a series of successful experiments, following precisely Morrison's scheme – one using electrified pithballs to attract letters written on strips of paper. As the story goes, it took ten to fifteen minutes to transmit one word, and two or three hours, one phrase. All in all, the road from the inception to the first experiment had been covered in twenty-one years. Nothing is known about the arrangement and length of the line used in the experiments. In all probability, Lesage's experiments, as most of the 'telegraphic' experiments of that time, were 'domestic in scale', as A. Yarotsky, a Soviet historian of the telegraph, has put it.

The first who thought of how to make insulated wires seems to be Iberio Cavallo (1749-1809), a physicist from Napoli. Under his scheme, an annealed copper or brass wire stretched taut was to be heated in the flame of a candle or simply by touching it with a white-hot piece of iron, given a coat of pitch, and wrapped with linen tape likewise uniformly smeared with pitch. Thus insulated, the wire was further to be protected by a woolen jacket. All this looked very much like the key components of a present-day cable: it had a conductor, an insulation, and a protective cover. The wire was to be made in sections six to nine metres long. The joints between the sections were to be carefully wrapped with oiled silk – quite a forerunner of the present-day cable coupler. Cavallo's idea seems to date back to the latter half of the 1780s.

The scientific community of that time took a curious stand (to say the least) towards all attempts to use electricity for telegraphy. As Professor J. L. Boeckmann of Karlsruhe wrote in 1794, "The prohibitive cost and other obstacles will never permit one to recommend the use of the electric telegraph". Oh, this notorious 'never'! How many times or, to be more correct, how many tens or hundreds of times it has appeared to be an unsurmountable obstacle in the way of discoveries and

inventions. And how many times, this 'never', seemingly so authoritative, has been refuted by the purposefulness and effort of a huge family of scientists and engineers and by their unflinching faith in progress. If Professor Boeckmann had lived some fifty years more after his publication, he would have been greatly astonished to see the telegraph picking up pace as it 'marched' across the world.

The early lines. In 1795, Don Francisco de Salvá (1751-1828), a Spanish physician (and not a physicist or an engineer as some books call him) reported his scheme of the electric telegraph and recommended his communication line to the Academy of Sciences at Barselona. He, too, proposed to use a separate pair of wires for each letter. But the most striking thing was this: "There is no need to keep the wires wide apart (recall Lesage's clay discs) – they can be twisted together into one strong cable, and laid in subterranean tubes. In my early experiments involving this type of cable, each wire was wrapped with pitch-treated paper. Then all the wires were twisted together and wrapped with many plies of paper. It was a good way to stop electricity from leaking off". That was the first mention of cable in the history of electric communication and, indeed, of all electrical engineering. Don Francisco de Salvá had anticipated the use of treated paper insulation by eighty years or more. He was the first to propose that the wires should be twisted together rather than placed in parallel. De Salvá did not propose any outer sheath for his cable, probably believing that the many plies of the outer wrap would be quite enough.

What de Salvá predicted further deserves special mention: "The cable can be made, or insulated, so that it would be impervious to water. Such cable could be laid at the sea floor, and it would be damaged very seldom". That was an amazingly accurate prediction! For de Salvá could not possibly know the material that would be used a half-century later for

insulation on the tens or even hundreds of kilometres of underwater telegraph cables laid in the seas and oceans throughout the world.

De Salvá's idea materialized in 1787 when A. Betancourt, a Spaniard, carried out experiments with Leyden jars and static electricity to send telegraphic messages over a distance of forty-two kilometres between Madrid and Aranjuez in Spain. Nothing is known about the line, what it was like, how it was used, and how long it operated. Most likely, it consisted of uninsulated (bare) aerial wires. In de Salvá's times, there were no machines yet to apply paper insulation to conductors. They came nearly a century later. On the other hand, it would have been a formidable task to insulate by hand the forty-eight wires, each forty-two kilometres long, a total of some two thousand kilometres. As our knowledge goes, a second line was built there in 1798 for personal use by the Royal family. Those were the world's earliest operational aerial or overhead communication lines.

Perhaps, it will sound a bit exalted, but we may say 'on the strength of the foregoing' (as they would say in an official document) that de Salvá was the true pioneer of electric, notably aerial, communication lines.

Jumping a little ahead, it may be noted that the next step forward in the development of communication lines was made nearly twenty years later. This bit was done by a London merchant, Sir Francis Ronalds (1788-1873). A proponent of the electrostatic telegraph, he began experiments in his garden in Hammersmith, a London suburb, in 1816, and made his results known to the public in 1823. Ronalds tried both an overhead and a buried line as the transmission medium.

He arranged the overhead line as follows. He erected two large wooden frames twenty yards (somewhat less than twenty metres) apart to serve as supports for nineteen horizontal bars each fitted with thirty-nine hooks. The hooks held a bare iron

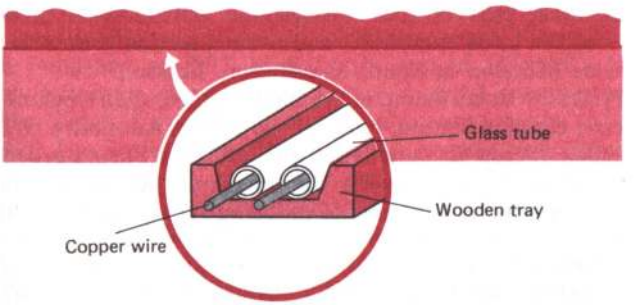


Fig. 2.9. The first experimental underground communication line installed in 1816

wire which ran from one hook to another, suspended on silk threads (the forerunners of insulators of the future). The total length of the single-wire line was no less than eight miles (about thirteen kilometres).

The installation included an underground run 175 yards (about 160 metres) long, laid in a trench four feet deep. In the trench he laid a pitch-treated wooden tray, a foot and a half wide. The trough carried glass tubes through which copper wires were threaded, and the tubes were joined together by glass sleeves, rendered water-tight with soft wax. At the top the tray was covered with tarred boards and a blanket of soil. That was a practical way of insulating buried wires, feasible at the time. A decade later its advantages were stressed by P. Schilling, the Russian inventor of the electromagnetic telegraph, in his report to the committee appointed by Czar Nikolas I to consider the construction of an electromagnetic telegraph line. Of all his predecessors, Schilling singled out Ronalds who had "proposed a new method of insulating metal conductors". The wooden trough and the glass tubes used by Ronalds were in effect a prototype of a cable insert in an overhead line.

In 1886, part of the underground portion was excavated – still in good condition – and a short section is now in the Science Museum at South Kensington, London.

Professor Boeckmann, as we have learned, didn't believe in electric communication. Nor did the British Admiralty. When Ronalds offered his system, he was told that Their Lordships were perfectly satisfied with the telegraph they already had, and there was no question of its being replaced by anything else.

HISTORICAL PARADOXES

The Coulomb Law which Coulomb didn't discover. Quite justly this law is ranked as the historically first law of electricity. By invoking it, we can say how strong the interaction (attraction or repulsion) between two charged bodies, such as two electrified pithballs, is. The force of interaction is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. This means that if we halve the original distance between two like (positive or negative) charges, the force of repulsion between them will increase four times. The law was experimentally established in 1785 by the French military engineer Charles Augustine Coulomb (1736-1806). Later it was named the Coulomb Law. The name of Coulomb has also been given to the unit of electric charge, or quantity of electricity.

Today we know that the basic law of electrostatics was first deduced, presumably in 1773, by the English natural philosopher and chemist Henry Cavendish (1731-1810), Fellow of the London Royal Society. But he never made his works on electricity known to the public. His manuscripts had been kept unknown in the library of the Cambridge University for over a

century before James Clark Maxwell (1831-1879), another eminent English mathematical physicist, found them. They were published in 1877, towards the end of Maxwell's life, nearly a century after Coulomb had announced his discovery.

Why didn't Cavendish make his discovery known to the public? The Soviet writer Daniil Granin in his novel, "Meditations in front of a Nonexistent Portrait", insists that "Cavendish's whim hid the blade of a challenge to those who succumb to the rush of narrow-minded pragmatism – publish, stake the claim as soon as possible so as to win in the contest".

This sounds a bit oversimplified. Cavendish's silence did retard the progress of science and Cavendish himself failed to discharge his duty of a scholar. The law he had deduced remained unknown, "a thing in itself" and not "a thing for everyone", for about a decade (it is a fact that Cavendish first applied himself to the study of electricity in 1771). But there is nothing immoral in the desire of most scientists to publish their findings and to stake their claims. As Michael Faraday (1791-1867), a highly distinguished English natural philosopher and chemist, remarked once, "The secret (of a success in science) is compounded in three words – Work, Finish, and Publish". Scientific activity is, among other things, competitive, not unlike athletics. In contrast to athletics, however, where the runner-ups also get their medals, there is only one prize to covet for in a scientific competition and nothing goes to those left behind. If Schilling of Russia hadn't made his brainchild known to the public in 1832, credit for the invention of the electric telegraph would have been given to Morse. Similarly, if Professor Popov, also of Russia, hadn't reported in 1895 his "device for detection and registration of electric oscillations", the priority for the pioneering work on radio would have gone to Italy rather than Russia.

Still, what was it that prompted Cavendish to act as he did? Was it overscrupulosity, a trait inherent in a true scholar more

than ambitions? For Cavendish was a great scholar, indeed. It is likely that he was not fully sure of his results and of their value to science. It is no less likely that he was distracted by his work in chemistry where he made quite a number of discoveries for which he was ranked among the founders of the chemistry of gases.

As the eminent Soviet physicist P. Kapitsa believes, Cavendish who, in the words of his contemporaries, was a shy and retiring man, simply forgot to send his paper to a journal or to communicate his discovery to anyone.

One way or the other, history will hardly throw any more light on the matter ever.

For many centuries up to 1785, only static electricity was known to exist. The Industrial Revolution which occurred in the eighteenth century came as a big shot in the arm for the many divisions of electrical science. Electricity was attracting an ever wider number of scholars, not only natural philosophers, but also physicians who thought they could use electricity as a cure. Among the latter was Luigi Galvani (1737-1798), Professor of Anatomy at the University of Bologna.

As history has it, the two students who assisted Galvani in his study into the nervous system of a frog in 1780 drew his attention to a strange thing. Each time they touched the femural nerve of a dissected frog with a scalpel, the legs of the animal would move convulsively. They believed this happened when sparks were drawn from the electrostatic machine which stood on the same table.

Highly intrigued, Galvani carried out several series of experiments which lasted for a total of ten years. In the first series, similar results were obtained on other animals and also when a spark was drawn from a Leyden jar. In the second, Galvani was after the effect of atmospheric electricity. He staged his experiments in the street. He would hang recently

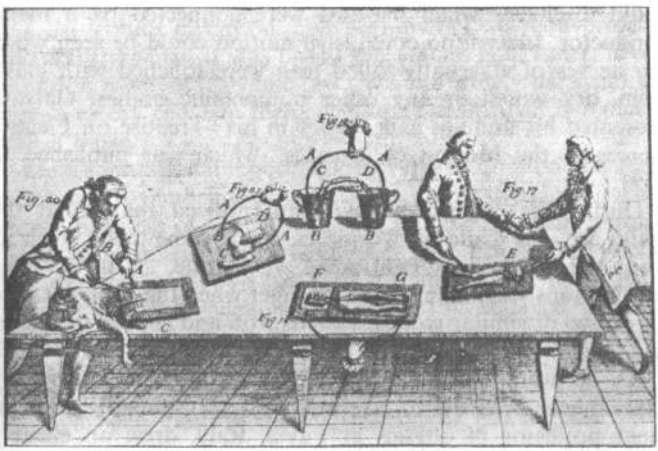


Fig. 2.10. Galvani's experiments with frogs

killed frogs by their femural nerves from a wire strung over his house, and connect their legs to another wire sunk in a water well. Each time there was a lightning discharge or storm clouds moved over the house, the legs of the frogs would contract frantically. However, Galvani saw the same thing happen with the frogs hung on copper hooks from the iron fence of his garden even in the absence of a thunderstorm, but he tended to explain this by changes in the state of atmospheric electricity. Before long, however, he realized that the state of the atmosphere had nothing to do with his observations, and resumed his experiments in his laboratory. Each time a metal arc was put between the muscles and nerves of a frog, the muscles contracted at once. From this he concluded that the frog itself could well be a source of electricity that accumulated in its muscles. As he reasoned, the muscles and the nerves could act as the two plates of a Leyden jar, and this

could discharge when the two were connected by a metal conductor. Indeed, no convulsive motion could be seen when the nerves of a recently killed frog were touched with glass, resin, dry wood, or any other nonmetallic bodies. Galvani presented his findings as a theory in his "Treatise on Electric Forces in the Motion of Muscles" which was published in 1791.

During his experiments, Galvani noticed that when the metal arc was made of two pieces of the same metal, such as iron, the frog's legs contracted very little, if at all. The contractions were many times stronger when the arc was made up of two dissimilar metals, such as iron and copper or, better still, silver.

As he went through and modified Galvani's intriguing experiments, Alessandro Volta (1745-1827), already a prominent professor of physics at Pavia, Italy, drew an entirely different conclusion from his observations. As he believed, the source of electricity was not the frog, but the contact between two dissimilar metals. As he wrote in 1793, "The frog's legs are nothing but a highly sensitive electroscope". A year later he wrote: "I have been certain for a long time now that everything arises from the metals, from their contact... Therefore, I feel I may ascribe all new electric phenomena to metals and use the name 'metallic electricity' instead of 'animal electricity'.

This started the historic dispute between Galvani and his supporters, on the one hand, and Volta and his school, on the other, on the origin of the electricity each had discovered. Journals and other scientific publications carried articles and notes under the flashy headings: "Electricity – Animal or Metallic?", "Galvani or Volta?". In the long run, Volta emerged victorious.

Volta crowned his experiments with the first continuous source of direct current which he built in 1800. The source consisted of a pile or stack of alternating copper and zinc discs

separated by cloth spacers moistened with acidified water or acid. In Volta's invention, chemical energy was converted to electricity. At first, it was called the voltaic pile. Later, it was given the name of 'galvanic cell'. We still widely use what are known as dry cells – in them, the liquid electrolyte is replaced with a paste.

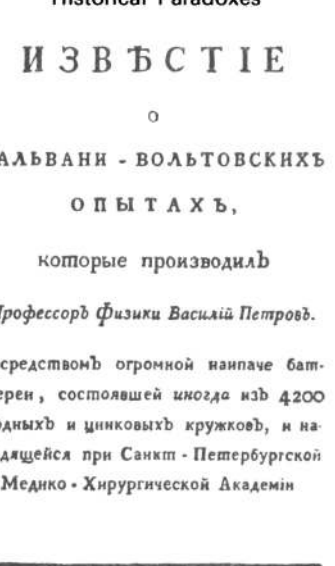
Volta's sensational reports and lectures in London and Paris in March-November 1800 came as an impressive closing scene for the progress of electrical science in the eighteenth century.

In the summer of the same year, the London physician Antony Carlisle (1768-1840) and a friend of his, the English engineer William Nickolson (1753-1815), engaged in their experiments with the voltaic battery, discovered what later came to be known as the electrolysis of water: as an electric current was passed through water, it decomposed into oxygen and hydrogen, both of them appearing as gas bubbles.

The voltaic arc which Volta didn't bring about. Some time after Volta's triumphs, V. Petrov (1761-1837), Professor of Physics at the St. Petersburg Academy of Medicine and Surgery, set out to build "a Volta pile so large that one would be enough to make a new experiment" which no one among the physicists had ever made. In April 1802, he assembled a Volta pile which consisted of 2100 each of copper and zinc discs. It measured twelve metres in length and generated an electromotive force of about 1700 volts. That was the world's largest source of direct current at the time. Using this battery in his study into the electric conduction of carbon, Petrov stumbled into an extremely important discovery in early 1802. He noticed that when he connected two lumps of charcoal with insulated leads to the opposite poles of his voltaic battery and brought them to within 2.54-7.62 mm of each other, a "very bright, white light or flame would appear between the carbons, and the carbons themselves would finally rise to a state of incandescence sufficient to illuminate a dark room

Fig. 2.11. Voltaic pile

rather bright". That's how he came upon the electric arc. Petrov summed up his findings in a book, "A Report on the Galvani-Volta Experiments Made by Vasily Petrov, Professor of Physics". That was the first Russian book on electricity; it appeared in St. Petersburg in 1803. Petrov did much to advance electrical engineering. His experiments offered a possibility to use electricity for lighting, metal smelting, and reduction of oxides (that is, ores) to metals. His investigation included the chemical effects of electric current, the electric conductivity of various materials, and the electric discharge in a vacuum. He demonstrated that metals could be electrified by rubbing, built electrostatic machines of his own design, and found that electric conductors could be insulated with molten sealing or bee wax. Nobody before Petrov had shown so clearly and forcefully the possibility of using electricity for



ИЗВѢСТІЕ

О

ГАЛЬВАНИ - ВОЛЬТОВСКИХЪ

ОПЫТАХЪ,

которые производилъ

Профессоръ Физики Василій Петровъ.

посредствомъ огромной напаче батереи, состоявшей *иногда* изъ 4200 мѣдныхъ и цинковыхъ кружковъ, и находящейся при Санкт - Петербургской Медико - Хирургической Академіи

ВЪ САНКТ-ПЕТЕРБУРГѢ

Въ Типографіи Государственной Медицинской Коллегіи, 1803 года.

Fig. 2.12. The title page of V. Petrov's book

practical purposes. He may therefore be ranked among those who have founded electrical engineering.

Petrov's name remained in the shadow for years despite the fact that his first book on electricity was "hot on the trail". In 1804, he wrote another book, "The New Electric Experiments". Unfortunately, this book was, as were his other books, in Russian and remained unknown to physicists outside Russia. As custom had it at that time, scientific works should be published in West European journals. As Daniil Granin

writes, "If Petrov's works had been published in a West European journal of physics, Russian science would have won much. Petrov's "Report on the Galvani-Volta Experiments" could have become available to physics the world over... It is a pity that Petrov's discoveries had to be restored, proved and defended a century later. He had the right, while still alive, to be ranked among the recognized builders of electrification".

It remains only to quote Faraday again: "work, finish, and publish". That's what any scientist should do at any time.

As the writer Daniil Granin remarks incisively and wittily, history has had own ways in giving out laurels: Volta's name was at one time given to the electric arc which he had never produced or seen himself, but the voltaic battery which was Volta's invention has finally come to be known as the galvanic cell. History has been especially generous towards Galvani. No other scientist can boast that his name has given rise to so many technical terms. We use galvanometers to measure electric current, galvanoplasty to produce shapes, galvanoglyphy and galvanography to print books and newspapers, and at least a dozen other things whose names include the name of Galvani. Volta's name has been given to the unit of electromotive force or potential difference – the volt. It has both multiples, the kilovolt (kV) and the megavolt (MV), and submultiples, the millivolt (mV) and the microvolt (μV).

TWO STEPS MORE

The electrochemical, or electrolytic, step. By the nineteenth century, the proponents of electric telegraphy had added two more things to their armory – the voltaic pile as a reliable source of electric current, and the discovery of electrolysis of water. With them, a new scheme that could be used for telegraphy was maturing. And again de Salvá, a veritable fountainhead of new ideas, was leading the field. At first (in

1800) he presented his treatise "On Galvanism and Its Use for Telegraphy" at the Academy of Barselona where he proposed to use frogs for the purpose. As de Salvá believed, telegraph signals could well be sent, using "the electricity supplied by a great number of frogs". These signals could, as he insisted, be received likewise by a frog. De Salvá backed up his idea by describing a 300-metre telegraph line which he had built and operated successfully. Lest the reader, on having read this story, should be eager to repeat de Salvá's experiments, let us pass on to his "Second Treatise on the Use of Galvanism for Telegraphy" which he read at the same Academy in 1804.

Now he proposed what may be called the 'bubble telegraph'. De Salvá had been experimenting with this project since 1802. A signal was to be sent by connecting a voltaic battery to a pair of conductors connected at the receiving end to a pair of metal rods inserted in a water-filled jar. There were to be as many pairs of wires and jars as there were letters in the alphabet. The bubbles appearing in a jar would identify the letter sent over the line. Later, de Salvá pointed out that fewer wires could be employed through the use of one common conductor instead of the second conductor in each pair. As a further refinement, he believed that the number of wires could be reduced by suitably combining the signals sent over several wires at a time. Then, as few as six wires would be enough for his scheme. Unfortunately, nothing has come down to us to tell if de Salvá was able to materialize his idea.

More luck in the advance towards what was called the electrochemical telegraph (now more commonly known as 'electrolytic') fell to Samuil Thomas von Sömmering (1755-1830), an anatomist in Munich. In 1809, he built an improved electrolytic telegraph in which the gold-plated ends of thirty-five wires were immersed in a common vessel filled with acidified water, rather than thirty-five separate jars. Using current of both polarities (that is, positive and negative),

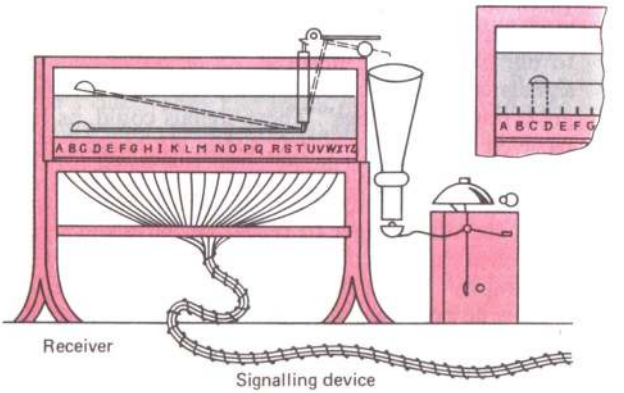
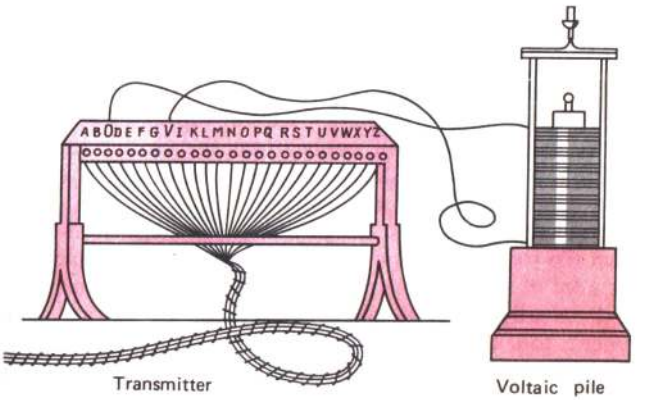


Fig. 2.13. S. Sömmering's electrolytic telegraph

Sömmering could send two letters at a time. At the transmitting end, one of the two wires was connected to the positive and the other to the negative terminal of a voltaic pile. At the receiving end, bubbles of hydrogen or oxygen were produced at the gold-plated lead, or electrode, assigned to the transmitted letter. The operator first wrote down the letter designation of the electrode producing more gas (hydrogen), and then the letter designation of the other electrode producing less gas (oxygen). The electrolytic telegraph could operate over a distance of six hundred metres. Sömmering used twenty-five wires to send letters and the remaining ten for numbers. In 1811, Sömmering devised coded combinations for signals and was able to cut down the number of gold-plated electrodes to eight. Now he could combine the electrodes in pairs, say the first with the remaining seven, the second with the remaining six, the third with the remaining five, and so on, and thus send as many as twenty-eight characters because that is the number



of combinations of eight wires taken two at a time, or mathematically

$$C_8^2 = (8 \times 7)/2 = 28$$

One more wire was used to notify the receiving end of an impeding transmission, and another wire was used as a common return. Thus there were ten wires in all. As Ludvic Souček notes, an attempt was made – for the first time – to insulate the wires with silk thread.

Sömmering made many experiments to test insulated wires and to investigate the conductivity of water. Taking part in them was Baron von Schilling who was an attaché to the Russian Embassy in Munich for nine years.

Many authors of publications about Sömmering's telegraph seem to neglect one intriguing fact. The German alphabet has twenty-six letters. Why is it then that the patent describing the first embodiment of Sömmering's telegraph mentioned only

twenty-five? The drawing in the patent also shows twenty-five letters, with the letter *J* missing. How should we interpret this? In explaining this insignificant but curious fact W. Mache, a West German engineer, has pointed out that telegraphy ordinarily used, as it does today, capital (upper-case) letters and, since in many German publications the Gothic letters *I* and *J* looked the same, Sömmering thought it would do no harm to drop the letter *J* altogether.

Although the electrolytic telegraph was an important milestone on the road to electric telegraphy, it proved impractical. It took a lot of time to transmit a single message, and the copy received usually showed quite a number of errors. The equipment, too, tended to fail quite often.

Nevertheless, the experience gained in the meantime was extremely valuable. Improvements were made in signal coding, component design, and wire insulation.

On the verge of electric telegraphy. The true electric telegraph was still two decades off. That span of time may rightfully be labelled with a single word – electromagnetism. The basic theory of electromagnetism was the brainchild of a whole constellation of scientists of world renown, mostly French. Among them, the brightest star was the famous André Marie Ampère (1775-1836), 'the Newton of electricity', as Maxwell, a brilliant physicist himself, called him later. (In fact, these same words might be applied to Maxwell himself.) But in order of time, their impressive file is headed by Hans Christian Oersted (1777-1851), Professor of Physics at the University of Copenhagen, Denmark. In the winter of the academic year 1819/20 (on February 15 according to some sources or somewhere in December according to others), he was demonstrating at his lecture how the electric current supplied by a voltaic pile could heat up a wire. To do this, he assembled an electric (or, in the parlance of that time, galvanic) circuit. One of the wires ran over the bowl of a mariner's compass which

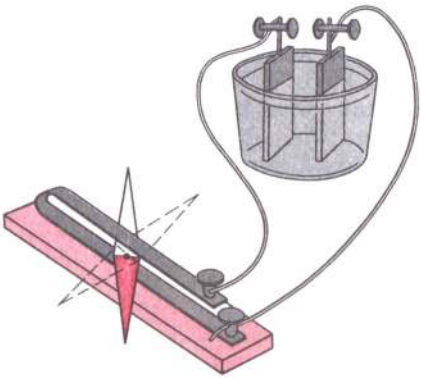


Fig. 2.14. Oersted's experimental setup

also stood on the demonstration table. Just as Oersted closed the circuit, one of the students (oh, those nosy students!) noticed that the compass needle swung aside. It did so again when Oersted opened and re-closed the circuit. That's how the action of electric current on the compass needle was discovered. (Actually, Oersted described his observation as the movement of electric fluid along the wire; the concept of electric current was to come later.) Again a fortunate and unexpected discovery? And again students, as in Galvani's experiments?

Yes, fortunate it was, but not unexpected. Oersted had put in eight years of pains-taking effort before the historic event happened. Already in 1812, while studying magnetism, he had thought of a relation between electric and magnetic forces, but he had had no convincing proof at that time. Now the proof was before him. It was set forth in the thin, four-page booklet that saw the light of day on July 21, 1820 and bore the title

"Experiments Concerning the Action of the Electric Conflict upon the Compass Needle".

Oersted used the words 'electric conflict' to describe the collision of two kinds of electricity. However, he failed to explain theoretically what he had established by experiment. This was done just two months and a half later by A. Ampère, Fellow of the Paris Academy of Sciences, who had learned about Oersted's experiments from Dominique Francois Arago (1786-1853), a friend of his.

A man of fantastic fate, a talented astronomer, a Spanish prisoner of war and an Algerian slave during the Napoleonic Wars, who wrote his scientific papers in prison cells and POW's camps, Arago came back to France at the age of twenty-three and was elected to the Academy of Sciences almost unanimously. As happened with Oersted, Arago grew, in the course of many years, aware that there should be some close relation between electric phenomena (especially lightning discharges) and magnetic phenomena. He, too, like Oersted, probably thought of establishing this relation. But, Oersted made it by a lucky chance, and Arago didn't.

A few days after Oersted's booklet was published, it fell in Arago's hands in Geneva. He repeated Oersted's experiments at once and reported his findings at a session of the Paris Academy of Sciences on Monday, September 4, of the same year. A week later, on September 11, Arago demonstrated Oersted's experiments to the members of the Academy. Among those present was Ampère.

Just a week later, on September 18, 1820, Ampère opened at the Academy a series of reports on electromagnetism. He was the first to propose the terms 'electric current' and 'strength of current' and introduced the concept of the direction of current flow – he assumed it (and this convention still holds) to be from the positive ("+") to the negative ("−") terminal, or pole, of a battery. He laid the foundation for electrodynamics, an entirely

new division in the science of electricity, encompassing all manifestations of a moving electricity. He established one of the basic laws of electrodynamics – the law of mechanical interaction between (attraction and repulsion of) electric currents.

He formulated a rule by which we can, even today, say where the compass needle will turn when acted upon by the current traversing a nearby conductor. In Ampère's time, it was known as the swimmer's rule: "If you mentally place yourself so that the current moves from feet to head and you face the compass needle, the current will always cause the North-seeking end to swing to the left".

In 1893, the scientific community gave Ampère's name to the unit of electric current. Even today, the ampere ('A' for short) is one of the seven basic units used in the Systeme Internationale – the International System of Units. Nor has Oersted been neglected – his name has been given to the unit of magnetic intensity.

The year 1820 was lavish with discoveries in the field of electricity. The French physicists Jean Biot and Felix Savart deduced a law, now bearing their names, to describe the interaction of a current-carrying conductor and a magnet in quantitative terms. J. Schweiger, Professor of Physics at the University of Halle in Germany, demonstrated that a current-carrying coil wound with several turns of wire could augment the action of the current on the magnetic needle placed inside it. His device came to be known as the multiplier.

In his third report to the Paris Academy of Sciences, Ampère came out with the idea of the electric telegraph. As he noted, "It has been proved that a magnetic needle placed far away from a battery can be caused to move with the aid of a very long wire". And he went on to say: "It would be possible, with the aid of wires, magnetic needles labelled with letters (there should be as many wires and needles as there are letters

in the alphabet) and a battery to transmit messages by sending telegraphic signals over the respective wires in a proper sequence. The scheme would offer a possibility to send messages over distances and across obstacles. At the receiving end there should be an operator to write down the transmitted letters by noting which of the needles have deflected". And finally, "Each letter would be transmitted in a span of time just sufficient to press the respective key at the sending end and to read the letter at the receiving end".

The decisive word in many years' relay of searches for a fast communication means was to be said by P. Schilling, a remarkable Russian scientist.

Chapter Three

Telegraph Cables Come First

SCHILLING, THE INVENTOR OF THE ELECTROMAGNETIC TELEGRAPH

Quite a lot has been written about P. Schilling, the famous Russian engineer, and the electromagnetic telegraph he invented. It is hardly possible to add anything more to the interesting and instructive books written by A. Yarotsky, a Soviet historian of science and technology. We will therefore limit ourselves to the highlights of Schilling's life and an outline of his epoch-making invention.

Schilling* was born in the city of Revel (now Tallinn) on April 16, 1786. After his term of instruction at the Military School and service in the Army, Schilling worked, from 1803 to 1812, as a translator and then as an attaché to the Russian Embassy in Munich. There, he came to know very closely S. von Sömmering and was active in his experiments with electricity. In 1811, Schilling followed up Robert Fulton's idea of detonating explosive charges remotely, using an electric fuse activated by a source of electric current over a pair of wires. In the autumn of 1812, when he was back in St. Petersburg, Schilling demonstrated his invention by setting off an underwater mine in the river Neva. In the demonstration he used an insulated wire of his own design, called "a subaqueous galvanic conducting cord" at that time.

In 1813-1814, Schilling saw front-line service with the Russian army and was awarded several high combat medals for bravery during the closing phase of the war against

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* Actually, his name was Paul Constadt, Baron von Schilling, but to his countrymen in Russia he was Pavel Lvovich Schilling.– *Translator's note.*

Fig. 3.1. Baron von Schilling, inventor of the electromagnetic telegraph in his China room

Napoleon. Then followed many years of his work with the Asiatic Department of the Russian Ministry for Foreign Affairs. When, in 1815, he was sent to Paris in the line of duty, Schilling went about among French physicists, and was on especially close terms with Ampère and Arago. He repeated his experiment by setting off an explosive charge with an electric fuse in the river Seine. By that time he had shown interest in a wide range of subjects: electric mines and telegraphy, Oriental studies and cryptography, lithography and cables. His findings in Oriental studies had made him so prominent in the field that he was elected, in 1828, to the St. Petersburg Academy of Sciences as a Corresponding Member in the department of literature and the ancient Orient. In 1830-1831 he headed a large scientific expedition to Eastern Siberia.

After he had first seen the electrolytic telegraph and learned about Oersted's discovery, Schilling spent twenty years looking for a viable method of telegraphy.

A prototype of what later was called the electromagnetic telegraph was completed and tested in 1828. That was a two-wire, single-multiplier apparatus. It contained all that was necessary to send and receive telegraph signals: a voltaic pile (or stack, as Schilling himself called it) as a source of power, a transmitter to connect any one of the two line wires alternately to the plus and minus terminals of the pile, a two-wire line, a transmit-receive switch, and a multiplier as the receiver.

The key element of the multiplier was a pair of astatic needles proposed by Ampère in 1821 to counteract the effect of the Earth's magnetism. The two needles were mounted on a common copper pivot and arranged in anti-parallel with each other: that is, their like poles pointed in opposite directions. The needles were suspended so that they were free to rotate in a horizontal plane, with one needle inside and the other outside a coil wound with several hundred turns of insulated wire. The silk filament which served as the suspension for the

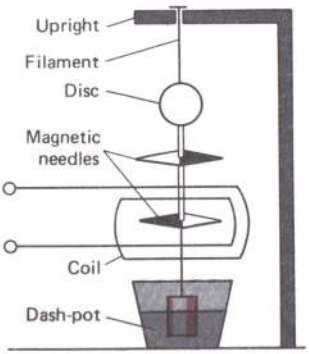


Fig. 3.2. The multiplier

needles also carried a disc about forty millimetres in diameter, painted black on one side and white on the other. The disc turned right to show its black (B) side or left to show its white (W) side according to the direction of current flow in the coil. When there was no current flowing, the operator could only see the edge of the disk. The free end of the filament carried a weight dipped in a dash-pot – a mercury-filled vessel which served to dampen oscillations of the needles.

Schilling devised a code to transmit the letters of the Latin alphabet and numerals. It consisted of combinations of one to five consecutive positions (B and W) taken up by the disc as a

A ○ | | | |	P | | ○ ○ | |	1 ○ ○ ○ | | |
B ● | | | |	Q | | ● ● | |	2 ● ● ● | | |
C | ○ | | |	R | | | | ○ ○	3 | ○ ○ ○ | |
D | ● | | |	S | | | | ● ●	4 | ● ● ● | |
E | | ○ | | |	T ○ | ○ | | |	5 | | ○ ○ ○ |

Fig. 3.3. Part of Schilling's improved telegraph code

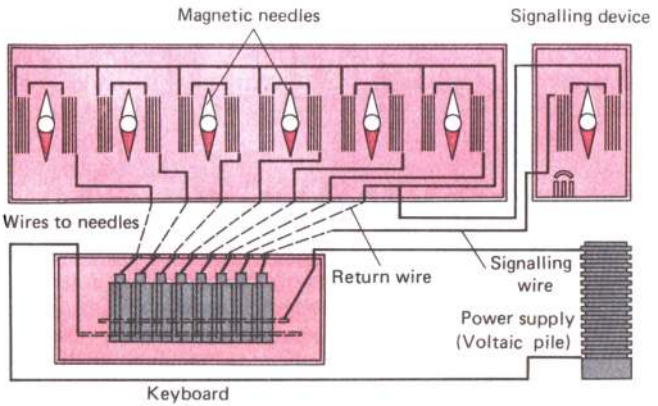


Fig. 3.4. Wire communication system using Schilling's six-multiplier telegraph apparatus

current of positive or negative polarity was sent into the line. As it turned out later, the code was not convenient to use: the operator had to keep in his mind the entire combination of consecutive disc positions in order to identify a letter. For example, the code combination for the letter A was 'black-white' (B-W), for the letter M it was 'white-black-white' (W-B-W), and for the numeral 5 it was 'white-black-black-white-white' (W-B-B-W-W). The transmission and reception of a message was obviously a very slow process.

The problem was resolved with the advent of a six-multiplier apparatus and an improved code. The letters of the alphabet were coded as the deflections (or, rather, positions) of the needles in one or two multipliers out of the six. The numerals were coded as the deflections of the needles in three out of the six multipliers. The entire arrangement was operated by a common transmitter which had eight pairs of black and white keys (one pair served to ring the called party and one pair was

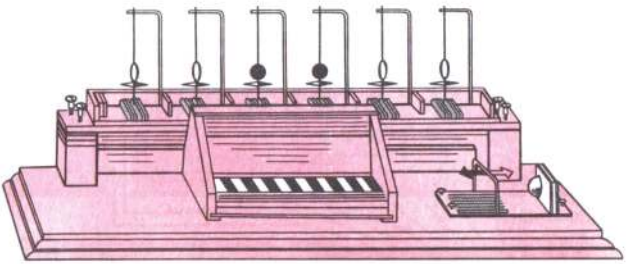


Fig. 3.5. Schilling's telegraph apparatus

common). There also was a common receiver with seven multipliers mounted on a single frame, with one multiplier intended to receive the ringing signal. The line part of the system had eight wires of which one was a ringing conductor and one served as a common return. Only five multipliers and a five-unit code were necessary to transmit and receive the Latin alphabet.

For the first time the new telegraph was shown to the public on October 21, 1832. The demonstration was arranged in Schilling's flat at 7, Mars Field, St. Petersburg. The transmitter was set up at one end of the flat and the receiver at the other, in what Schilling called the China Room and used as his study. The distance between the two sets was a little more than a hundred metres. The first telegram which consisted of ten words was received by Schilling himself – without an error and instantly – in sight of those present.

Despite the obvious public interest in Schilling's invention, the government was not in a hurry to put it to practical use. In September 1835, Schilling demonstrated his telegraph in operation at a Congress of Natural Philosophers and Physicians (the Department of Physics and Chemistry) in Bonn. It was not until 1836, however, that the Russian

government appointed a commission "to consider the electromagnetic telegraph", with the Navy Minister as its chairman. The Commission instructed Schilling to set up a telegraph line in the Admiralty's building for long-term tests under conditions close to those that could be anticipated in actual service. The sets were installed in the opposite ends of the Admiralty's long building, and the wires were laid partly in the ground and partly in water. In May 1837, the Commission instructed Schilling to install a telegraph line between Peterhoff and Kronstadt. The inventor was to draw up all the necessary plans, specifications and cost estimates, but he failed to do that – he died in the summer of 1837.

EARLY CABLES – THEIR FIRST AND LAST DEFEAT

Schilling was the first who took a practical approach to the problem of underground cables capable of carrying electric current over a distance. Of course, both Winkler and de Salvá had come up with innovating ideas which were a good deal ahead of their time, but their ideas had remained what we may call a scientific foresight or a prediction. Sömmering had used a bundle of silk-insulated wires for his impractical room telegraph, but he had never tried to use his line 'outdoors'. Obviously, Schilling could not use a wire with such an insulation which would eagerly take up water and lose its dielectric properties.

When Sömmering and he were testing insulated wires buried in soil and laid under water, it occurred to Schilling in 1811 that it would be a good idea to water-proof the insulation. At first they used a wrapping which consisted of several plies of silk yarn given a coat of earth wax. Thus insulated, the wires could operate trouble-free even after a day in water before the tests. Soon Schilling improved the insulation. That's how he

described it: "The wires consist each of several fine copper filaments wrapped with silk, given a coat of caoutchouc and plaited into hemp cords". Note the word 'caoutchouc' (unvolcanized India rubber) – we will go back to it later.

In his report about his invention in 1827, Schilling wrote that he "has got such a wire two hundred feet long and four inches in diameter, which was made in 1813 and has passed close on a thousand tests. This wire has been kept buried in ground for six months, in a silt-laden pond for a summer, and in snow for two winters, and is still good and fit for service".

The make-up of the wire was as follows. The copper conductor one or two millimetres in diameter had a double wrapping, inner and outer. The inner wrapping was made of coarse silk or cotton thread, and the outer wrapping was of hemp yarn. After the first ply of insulation was applied, the conductor was immersed for impregnation with a solution of India rubber in linseed oil. After drying, it was given another ply of hemp and impregnated in the same solution for a second time. Thus treated, dried and painted with varnish, it was ready for use. Because the outer wrap was made of hemp yarn, Schilling often called his conductor the cord. That's how he described his line set up around the Admiralty's building: "The twenty cords used as conductors and joined to one another total between them a little more than ten miles."

However, the insulation of the wire that was to be used only once to detonate an underwater mine didn't have to meet stringent requirements. The only pulse of current needed to set off an explosive charge could well be transmitted over a wire with a poor insulation (and, as a consequence, with a good deal of current leaking off), using a bigger battery. The wires used to detonate a mine had to stay in ground or water for a very short time.

(Even today, the leads used in commercial blasting work are the most primitive among nearly a thousand cable products:

soft copper wire 0.5 or 0.8 mm in diameter is given a coat of polyethylene insulation 0.35 or 0.6 mm thick respectively; each lead can be made of one or two insulated wires twisted together.)

It is quite another matter with a telegraph line which is laid to serve for many years.

In 1881, visitors to the International Electrotechnical Exposition in Paris could see the telegraph cable invented by Schilling – it consisted of "eight copper wires each of which is insulated with a coat of India rubber, and they all are wrapped with hemp impregnated with India rubber". We will see later in this book that Schilling's product was not yet a cable in the present-day meaning of the word.

At first, Schilling was highly optimistic about the reliability of his cable. He believed it would be able to convey electricity "from one station to the next, no matter what distance between them. It will not succumb to dampness or changes in temperature. It is flexible enough to avoid rupture and, buried deep in the ground along major roads, it could readily be watched, as it were, by all travellers". As to 'watch' over a cable buried deep in the ground, Schilling was surely wide off the mark. As to the reliability and durability of the cable's insulation, Schilling did not limit himself to conjectures. He went on with his research into how various types of insulation could be compared without personal bias. In 1836, he tested short lines laid in the ground, under water, and in the air.

There was no way of measuring the electrical characteristics of cables in Schilling's time. Nevertheless, he found that even the insulation of the best cable laid in the ground or water lost its properties very quickly. In this, it was inferior to the 'air' insulation of the bare wires strung on insulators between wooden poles. That was the reason why, in contrast to the design approved by the Commission, Schilling insisted that half of the line from Kronstadt to Peterhoff was to be in the

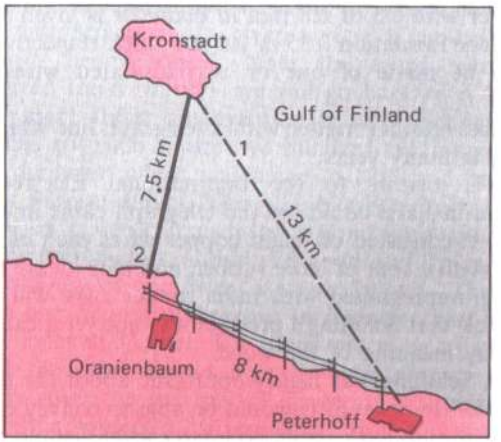


Fig. 3.6. Contemplated telegraph line between Peterhoff and Kronstadt, Russia: *1*, the route approved by the Commission; *2*, the route proposed by Schilling

form of bare conductors strung on poles to be set up along Peterhoff Road. His idea of an overhead, or aerial, line was turned down. For one thing, the Commission thought it was too 'phantastic'. For another, the government didn't wish to lift the veil of secrecy off the new communication means. As B. Yacobi, Schilling's friend, companion and follower, who was present at the Commission's meeting, recalled, Schilling's reasonable proposal met with hostile and derisive cries from Commission members. One of them told Schilling later, "My dear, your proposal is a folly, and your aerial wires are simply preposterous."

As Yacobi wrote after his journey outside Russia in 1850s, "Now that the greater part of Europe and the United States is covered with a huge network of aerial lines, we must pay a

tribute of respect to Schilling who came up with a similar scheme for the electric telegraph back in 1835 and 1836."

After Schilling's report in Bonn, his telegraph drew attention in Western Europe. In April, 1836, Karl August Steinheil (1801-1870), an eminent Bavarian physicist and optician, applied to the authorities for money with which to build an electromagnetic telegraph line over a distance of five kilometres between Munich and Bogenhausen. Unfortunately, he failed to build the underground line he had proposed, and switched, in 1837, to an overhead line, with the wires strung partly between the rooftops of tall buildings and the spires of some churches, and partly between wooden masts set up 350 metres apart.

During March of 1836, William Fothergill Cooke (1806-1879), who had just been invalided out of the East India Army, was in Heidelberg where he was studying anatomy at the local university. Quite by chance, he happened to attend a lecture read by G. Muncke, professor of physics, that same Muncke who, just six months before, had presided at the Congress in Bonn where Schilling demonstrated his telegraph. Impressed by the invention, Muncke explained to the students how the electromagnetic telegraph worked. Cooke got hold of an instructional three-multiplier apparatus (by bribing, to believe Souček, the mechanic who had built the set for the university), and hurried back to England to put his trophey to commercial use. However, his knowledge of science was rudimentary, and Cooke needed an electrical expert who could help him in his enterprise. The man he contacted was Sir Charles Wheatstone (1802-1875), a celebrated physicist and electrician, Fellow of the London Royal Society and Professor of Natural Philosophy at King's College, London. I'm sure every schoolboy knows what the Wheatstone bridge, a device used to measure electrical resistance, is like. It took very little time for Wheatstone to realize that the three multipliers would not be

enough to transmit all the letters of the English alphabet. Wheatstone and Cooke formed a partnership, built first a four-needle instrument, then a five-needle apparatus and filed their first patent application on June 12, 1837. They did what Schilling had not. (It is very likely that he obeyed Emperor Nickolas I's ban to publish any particulars about the equipment used for electric telegraphy.) That was how the world learned about the electromagnetic telegraph patented by Wheatstone and Cooke and since then known as the Wheatstone-Cooke telegraph. Actually, except for a few minor details, it differed very little from the Schilling telegraph.

Meanwhile, the enterprising Cooke asked the Russian government "how much they would be prepared to pay him for the possibility to transmit fifty words, of five letters each, every ten minutes from St. Petersburg to Moscow?". Technically, that was an interesting proposal – to transmit 250 characters in ten minutes over a line 650 kilometres long. Already in its infancy, the new invention was capable of transmitting messages at a rate five times faster than could, over a comparable line, the then well known semaphore.

Soon Wheatstone and Cooke set up what they called the Electric Telegraph Company and netted fortunes in royalties. Railways were the first to take interest in the telegraph. Trains of that time could travel at a speed as high as sixty kilometres an hour. Naturally, railway management needed a communication facility that would be able to transmit messages between stations faster than a train could cover the distance. As railway companies stated in their specifications for new railways, "There shall be a telegraph communication facility, arranged in the direction of railways, to provide a means for traffic control and thus to prevent the accidents that might occur, should trains collide".

A demonstration telegraph line using five-needle instruments was set up in 1837 along the one-mile Euston-Camden

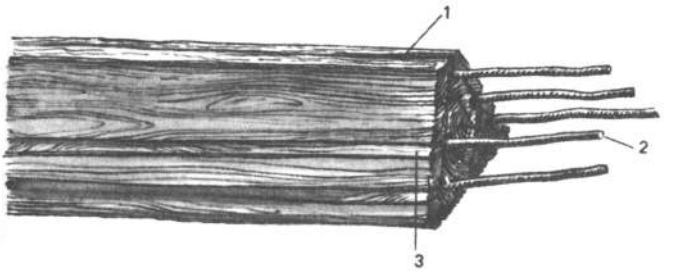


Fig. 3.7. Construction of an early underground telegraph line: *1*, impregnated wooden balk; *2*, copper wires; *3*, wooden strips

Town section of the London-Birmingham Railway. The five bare copper wires were laid in grooves made in wooden balks of trapezoidal cross-section. The grooves were plugged with wooden strips, the balks were painted with liquid wood tar to prevent rot, and the whole installation was laid in a trench covered with pitch. Probably, the line failed because the directors of the railway were not convinced and later gave preference to the pneumatic whistle pipeline in use at the time.

Anyhow, the first commercial telegraph line, using five-needle instruments, went into service on July 9, 1839, on the Great Western Railway, linking Paddington Station in London and West Drayton, a distance of twenty-one kilometres. In 1843, the line was extended to reach Slough; now it was fifty kilometres long. It was built with wires insulated in some unknown way and drawn into iron pipes. What is known is that the line operated successfully until 1845 or, perhaps, some later time.

The telegraph proved its worth in one more, rather unusual way, when on January 1, 1845, the operator at Paddington Station received a telegram from Slough. It informed him that a murder had been committed and that the suspect boarded

the 7:42 train to Paddington, sitting in the last compartment of the second 1st-class carriage. Policemen waited for him at Paddington Station, and when John Tawell, the murderer, was later hanged, the telegraph had indeed become the talk of London.

A physicist and an electrician, equally strong in both theory and practice, B. Yacobi (1801-1874) was fifteen years younger than Schilling. Their acquaintance, started in 1836, soon grew into the friendship of persons holding the same views. In 1837, Yacobi stayed at Schilling's for several months. Yacobi is credited with the invention of galvanoplasty, pioneer work in electrical measurements, and several electric motor designs. After his friend's death, Yacobi did much to carry on Schilling's ideas in electric telegraphy. Among other things, he designed, in the 1840s and 1850s, over a dozen types of telegraph apparatus and built several underground telegraph lines.

Later in this book we will see how early underground electric telegraph lines evolved. Here, jumping a little ahead, we can only note that Yacobi in 1846, much as Schilling did in 1837, realized that underground cable lines had no future at the present state of the art and that overhead wire lines offered a far better choice.

About the same chain of events took place on the other side of the Atlantic – in the United States of America. In 1844, work started on the first underground telegraph line designed by Samuel Finley Breeze Morse (1791-1872) who soon gained international renown. The line, some sixty kilometres long, was to connect Washington and Baltimore. At first an attempt was made to lay a multiconductor cable enclosed in lead pipes. Ezra Cornell, an American engineer, developed a plough which could dig a trench, lay a cable there, and finally fill it up with soil. That was the world's first cable-laying machine. However, the effort ended in a failure in about ten miles from the start, as

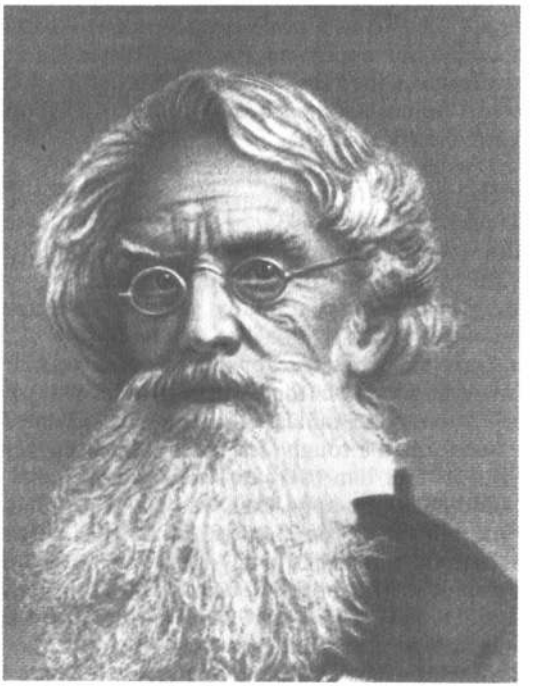


Fig. 3.8. Samuel F. B. Morse, inventor of the telegraph code and printing telegraph

T. Avery, Morse's helper, recalled later. It was caused by many short circuits. Around April 1, 1844, Morse and his team switched to wires strung on wooden poles, using the necks of glass bottles as insulators. (There was a joke that they used whiskey bottles.)

Although to most people Morse is known as just an inventor, he was far more than that. He graduated at Yale in

1810 and adopted art as a profession. He gained distinction as a sculptor and was appointed Professor of the Literature, of Arts and Design at the New University of New York. Later he was elected President of the Academy of the Arts. Throughout those years, electrical studies were his hobby. But it was his hobby that won him world renown.

In October 1832, that is, at about the same time as Schilling demonstrated his invention for the first time, Morse learned about the amazing effect of electric current on a magnetic needle. This prompted him to build a telegraph. As with Schilling, Morse had spent many years of strenuous effort before he could reach his goal.

In contrast to Schilling, however, Morse was, from the outset, after a telegraph that would produce a permanent record of, rather than indicate, the transmitted message. By 1835, he had formed a rough idea of what his telegraph should be like. But it took him two years more to assemble his first apparatus. Finally, the apparatus was put to a public test at New York University on September 4, 1837, with Morse sitting at one end and his partner, Alfred Vail, at the other. The first telegraphic message read: "Successful test of the telegraph 04 September 1837". But that was hardly a success. The electromagnet-operated pen of the apparatus wrote the incoming signals as jiggles on moving tape which the inventor himself was hard put to read. The code proposed by Morse was too cumbersome. The spectators ridiculed Morse, but the failure didn't discourage him. In a matter of four months he had improved his apparatus and devised an entirely new code, a combination of dots and dashes, his now famous Morse code mankind has been using for a century and a half. The new test staged at the same University on January 24, 1838, was a success, indeed. This time, however, Morse used a line about ten miles long for transmission. Another five years went, however, before Congress granted, by an eighty-nine to

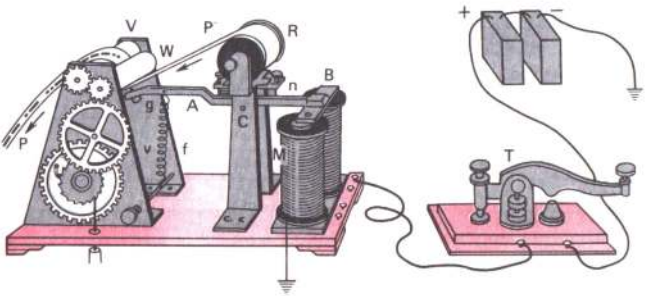


Fig. 3.9. Morse's telegraph apparatus

eighty-three vote, funds for an experimental line between Washington and Baltimore. Late in May, 1844, the overhead line went into operation.

Sometimes it is argued that Morse invented an 'electromagnetic' telegraph. That's not accurate. The 'electromagnetic' telegraph, that is, one operating on the principle of electromagnetic interaction, was invented by Schilling. A good deal of confusion comes from the fact that the word 'electromagnetic' is sometimes used to describe the principle of operation and sometimes to indicate the use of an electromagnet in the telegraph apparatus. The point is that while Schilling used a multiplier, and Wheatstone and Cooke a magnetic needle instrument for the receiver, Morse chose an electromagnet invented by the English self-educated electrician William Sturgeon (1783-1850) in 1825 and later improved by Joseph Henry (1797-1878), an American physicist of great renown, who advised Morse on many occasions.

What was the Morse apparatus like? There was an electromagnet, *M*, whose armature, *n*, was one of the arms of a lever which was free to rotate on a pivot, *C*, while the other arm, *A*, acted upon by a spring, *f*, had at its end a pen, *g*. Pressure on a

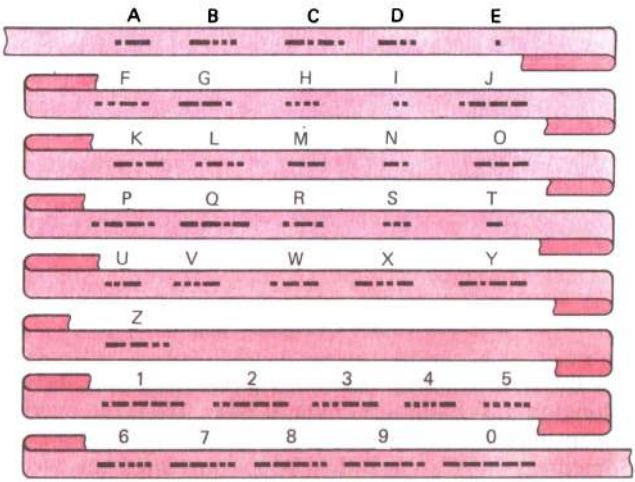


Fig. 3.10. Morse code

key, *T*, would complete the electric circuit, and a current supplied by a battery would energize the coil of the magnet with the result that the armature *n* would be attracted to the magnetized iron core, *B*. The lever arm *A* would go up, and the pen *g* would write either a dot – if the key was held closed for a short time, or a dash, if the key was pressed for a longer time. The dots and dashes were written on a paper tape, *P*, advanced at a uniform pace from a feed roll, *R*, by a clockwork and two rollers, *V* and *W*.

Simple, compact, easy to manipulate in both transmission and reception, and fast in operation, the Morse telegraph remained the most commonly used type in many countries for over a half-century. An important thing about the Morse code is that the most frequently occurring letters were assigned

shorter code combination than those occurring less often. This can readily be seen from Figure 3.10. How often the letters of the English alphabet occur in texts in terms of the letter *Z*, as found by Morse himself, is given below:

Z–1	P–8.5	U–17	O–40
X–2	G–8.5	L–20	N–40
J–2	Y–10	D–22	I–40
Q–2.5	W–10	R–31	A–40
K–4	F–12.5	H–32	T–45
V–6	M–15	S–40	E–60
B–8	C–15		

Starting in the mid-nineteenth century, the telegraph spread throughout the world at an ever quickening pace. In 1855, the telegraph lines in Europe totalled between them forty thousand kilometres, with Russia accounting for nearly six thousand. Five years later the figure doubled to nearly eighty-four thousand kilometres, with France ranking first (twenty-two thousand kilometres), Russia second (over seventeen thousand), and Britain third (with a bit less than Russia). In 1865, Europe had a total of 150 thousand kilometres of telegraph lines, with Russia topping the list (over thirty-five thousand kilometres), France coming second (over thirty-one thousand) and Britain third (over twenty-five thousand). In 1871, the Moscow-Vladivostok line, around twelve thousand kilometres long, the longest at the time, went into operation.

After failures with early underground cable lines, almost all telegraph traffic (97-99%) in all countries was handled by overhead wire lines. Short cable sections would usually be inserted in a telegraph line where it had to cross a railway, a lake or a river, and only seldom in cities. However the length of telegraph lines does not tell the whole story – telegraph traffic was growing faster than the line length. Therefore, several (three to five or, sometimes, eight to ten) bare

conductors would be strung on pole supports. The conductors were usually made of low-carbon steel (or iron, as was the custom to name the material at that time). The diameter of the wires fabricated from 'top-quality iron' would be two and a half, three, four, five and six millimetres accurate to plus or minus 0.1 millimetre.

Put together, all the individual circuits totalled in 1865 over 425 thousand kilometres in Europe alone. This was three times the length of the lines.

It is interesting to look at Russia's telegraph statistics of that time. In 1881, the country had close on ninety thousand kilometres of overhead telegraph lines and 1083 telegraph stations. In that same year, they transmitted a total of 7.3 million messages. In 1883, the number of stations grew to 1372 and the lines totalled ninety-seven thousand kilometres. They used, between them, nearly 180 thousand kilometres of wire. In that year, the number of messages transmitted by the telegraph was 10.22 million, which works out to an average of ninety-eight per thousand population. Thus, telegraph traffic had increased by forty per cent, and the line length by eight per cent. An overall picture of progress in telegraph communication can be gleaned from Table 1.

Before the large-scale spread of telegraphy, only one wire was needed to set up one telegraph connection (or, as is usual to say now, one telegraph channel). Setting out with four-needle instruments, then switching to the five-needle type, Wheatstone and Cooke finally adopted in 1840 a two-needle design. In 1845, they devised a code so that a single-needle instrument could be used. With it, two wires were needed to set up a telegraph circuit. But, as with the Morse telegraph, one of the wires could well be dropped by using the ground as the other (return) wire. It was C. Steinheil who was the first to prove this possibility. After his failure with an underground telegraph line and also because the Bavarian government did

Table 1. Length of Overhead Telegraph Lines (thousand kilometres)

Continent	1866	1900
Europe	180	2840
America	80	4050
Asia	20.8	500
Australia	3.2	140
Africa	—	300

not want to build overhead lines, he tried, not without a success, to use railway tracks for the purpose.

He made his experiments on a 30-kilometre section of the Nürnberg-Fürt railway. One day, when he was driving down the road next to the railway, he noted that the track was dismantled for about a dozen metres because repair work had been going on there for several days. He was greatly surprised to learn that the telegraph was operating as usual. Quite logically he concluded that, since the track was dismantled, the only path remaining for the current to flow was through the ground. That was how it was discovered that electric conduction through earth could be used for practical needs. In 1838, Steinheil made public a paper in which he proposed to use the ground instead of a return wire in telegraph circuits, but over short distances only. Again a freak of chance ? Isn't it time for us to start a score of all the unexpected but fortunate discoveries we are going to read about in this book? But again chance presented itself to a man who had been searching for an answer.

As a result of the many experiments on the 25-kilometre St. Petersburg–Czar Village line (among the longest underground cable lines at that time), Yacobi showed that electric conduction through the ground could be used over any distance,

Table 2. Conductivity, S/m, of Some Materials

Material	Conductivity
Conductors:	10^8 to 10^5
copper	5.8×10^7
aluminium	3.5×10^7
steel	1.0×10^7
Semiconductors	10^6 to 10^{-9}
soils	10^{-1} to 10^{-3}
Dielectrics	10^{-7} to 10^{-17}

Note: Electrical conductivity has the units of siemens divided by metre ($1\,S = \Omega^{-1}$).

however large. As he wrote in 1843, "Measurements on the Czar Village line have shown that half of the telegraph circuit could well be dropped and that the ground could well take over".

Of course, earth is not as good a conductor of electricity as metals. Its electrical conductivity is one-thousand millionth or even less than that of metals. Still, it is high enough for electric current to flow through soil. That is why, since practically their conception, all telegraph lines, both overhead and underground, have operated as single-wire circuits. The second, or return, wire was earth (when a line was set up on land) or water (if a line was laid in water).

HAS CABLE EVER BEEN INVENTED?

Sometimes history is as accurate as a pedantic clerk – it will meticulously record the date and the essence of a discovery or of an invention and the name of its originator. That's how it

has happened with the telegraph, the telephone and radio. On other occasions, history seems careless, so nobody can say who was the first to discover or invent something. As often as not, however, history is not simply able to keep its records straight if a discovery or an invention has been the outcome of a gradual process of minute changes. This fully goes for communication cable.

Before we go any further, however, it's time to introduce the reader to the key terms used in connection with cables. As Pythagoras (the sixth century B.C.), a celebrated Greek philosopher and mathematician, allegedly said once, "Above all learn to call every thing by its proper name". Despite this adage, however, it was not until the latter half of the twentieth century that terminology established itself as a science. As L. Fink of the USSR notes in his "Signals, Noise, Errors", it is widely held that a scientist's stand towards terms depends on his age. Younger scientists, he says, tend to neglect the purity of terms; the very fact of the advent of something new is more important to them. In contrast, he goes on, elderly scientists, as their creative activity loses its drive, tend to attach a greater, sometimes improportionately greater significance to terminology. As this author believes, however, this is not a matter of age, but one of the sense of duty. There have been young scientists who were extremely careful in choosing a name for a new thing. On the other hand, there have been the older members of the scientific community who were entirely indifferent to the matter.

Well, a communication cable is an electrotechnical product which can be installed everywhere, that is, in the ground, under water, in the air, or indoors, and used for the transmission of appropriate signals. Until quite recently, only electric signals would be meant, but now this term also includes optical (light) signals. A cable consists of two or more (as many as several thousand in some cases) insulated conductors stranded in a

certain manner and encased in a common sheath. (Single-conductor cables were used in the nineteenth century as well.) The conductors are fabricated of highly conductive materials for ease of current flow, and are insulated from one another to avoid interference. When stranded as required, the conductors make up the cable core – the heart of a cable. Indeed, the Germans call it, a bit poetically, 'Kabelseele' and the French, no less poetically, 'Ame du cable', that is 'the soul of a cable'. The sheath, which may be made of metal or plastics, protects the conductors against exposure to a host of 'enemies', above all moisture. Curiously enough, submarine telegraph cables quite often do without any sheath. Many underground cables will, on the other hand, have an additional armour over their sheath.

What sets a cable apart from a wire? As a rule, a wire will not be intended for installation under the ground or under water and will therefore have no substantial sheath – this is the most important of its distinctions as compared with a cable. Protection against exposure to the environment is provided by light-weight plastic tubing or fibrous (cotton, silk, or synthetic-fibre) wrapping or braiding.

Now that we have learned a few terms, we are in a position to say that Schilling invented a wire, and not a cable. At first he had to do with single-conductor wires for communication and double-conductor wires to detonate explosive charges. The conductors, although insulated from each other, were not twisted together – there were no machines to do the job yet; they were simply held together and protected by a common impregnated hemp wrap. Of course, this sort of sheath could not offer a long-time protection to the silk insulation which would eagerly absorb water even when given a coat of varnish. As Schilling had found, his wire could stay in the ground intact for six to twelve months. He judged solely from the external appearance of the wire because there were no ways and means

of assessing the electric or, rather, dielectric properties of the insulation, yet. It is a safe guess that if his wire had been left lying in the ground for two or three years, its insulation would have rotted completely. Schilling seems to have been the first to use unvolcanized India rubber for insulation. At first, he treated the silk insulation of the conductors and the outer sheath with a rubber compound in much the same way as in making mackintoshes – rainproof coats made of cloth treated with rubber, and named so after their inventor Charles Mackintosh.

Later, as we read in Schilling's notes, he thought up to apply raw, unvolcanized rubber mass over the silk insulation by hand (there were no machines to do the job, either). Although raw rubber, as made at that time, could protect the insulation against picking up moisture, it would do so under certain conditions only. As the temperature rose in summer, the material would soften, become sticky, and tend to flow. In fact, the insulation would be simply smeared with raw rubber. There was another way of insulating wires. Wrapped in yarn, a wire was dipped in a hot paste made up of beewax, tallow, pitch and other ingredients (various compositions were tried). Following that, the wire was again wrapped in yarn and smeared with the same paste.

As early as 1836, Davy, the namesake of the great English chemist Sir Humphry Davy, proposed to draw wire insulated with impregnated silk into pipes. In 1840, Wheatstone used cast-iron pipes for his thirty-kilometre telegraph line in England. There were proposals to use asphalt or clay pipes instead of iron ones and to bury them in the ground at a depth of a yard.

As with other 'telegraphers' in the 1840s, B. Yacobi was well aware of the need to provide a reliable protection of the 'soul of the cable' against the whims of the surroundings. As he unambiguously stated, "Pipe conduits are indispensable not

only because the insulation might prove at fault, but also because the wire can readily be damaged if it is easily accessible".

Yacobi built his first telegraph line in the autumn of 1841. It was a two-wire line 363 metres long, which ran from the Winter Palace across Palace Square to the General Staff building in St. Petersburg. The soft copper conductors three millimetres in diameter were insulated with two plies of cotton yarn impregnated with a compound made up of wax, tallow and rosin. Thus insulated, the conductors were enclosed in a string of slim tinplate sleeves. Yacobi was dissatisfied with his idea. As he wrote, "We ran into a host of inconveniences with the pilot line laid under Palace Square. Instead of pipes, we used sleeves shaped from tinplate and inserted into one another in a stovepipe fashion". The sleeves failed to protect the wire insulation against ingress of moisture at the joints.

An eminent electrician of his time, Yacobi was well aware of the low quality of wire insulation and realized its shortcomings. In an attempt to avoid current leaks, he did quite an extraordinary thing. As he wrote, "Since galvanic leaks occur under the ground, I chose glass tubes although this material had hardly been used for my purpose before and there seemed to have been no past experience to draw upon". Apparently, Yacobi did not know about the glass tubes used by Ronalds in his electrostatic telegraph or thought it was of little significance because of its small size.

In 1842, Yacobi built a second line. Running for over two and a half kilometres, it linked the Winter Palace with the Chief Railway Board. Instead of tinplate sleeves, he used glass tubes twenty millimetres in diameter and one and a half to two metres long. That is how Yacobi described his line: "The glass tubes were slightly ground at the ends and joined with rubber couplers so that the line could readily follow every bend of the trench. At first, the tubes were laid at the bottom of the trench

Fig. 3.11. B. S. Yakobi, a prominent Russian electrician

and bricked up at the anchoring points. Later, no brick was used, and the tubes were laid on a bed of fine-grained sand fifteen centimetres deep and covered with another bed of the same sand carefully screened to remove stones. The trench was fifty-five centimetres wide at the bottom." As he added, "Of course, a better way would have been to enclose the glass tubes in a wooden jacket, but this would have added too much to the

project's cost. Also, wood readily picks up moisture and would fail very soon." Unfortunately, the new experience could not be used – glass tubes had to be abandoned because they were too fragile.

In England, an underground line was laid in creosote-impregnated wooden balks which had square slots. These wireways could each carry as many as ten wires and had a wooden lid; later galvanized steel covers were used for the purpose. Where the streets had a cobblestone pavement, the wires were pulled inside three-inch gas pipes.

A different way to install an underground telegraph line was used in Paris in 1855-1857. A trench 1.2 metres deep and 90 centimetres wide was dug, and ten wires were stretched taut for a distance of sixty to eighty metres. The wires were anchored in place by iron combs with their teeth spaced an inch apart. The bottom of the trench was covered with a sheet of sturdy paper, its walls were shored up with boards, and vertical bars were installed in it at regular intervals. The structure was not unlike shutterings or forms used to pour concrete in place. It was then filled with a mixture of two-thirds asphalt and one-third washed gravel. After the mixture solidified, the iron combs and the boards were removed to leave the wires insulated from one another inside the now covered trench. Interestingly, the conductors were made of galvanized steel wire four millimetres in diameter rather than copper. The insulation was cotton yarn treated with shellac.

A funny way (by present-day standards) was used to install the twenty-five kilometre underground Alipur-Rajghat section of the Calcutta-Kedgheri telegraph line in India. The conductors were iron rods four yards long and about four inches in diameter. Each rod was secured to bamboo poles three feet tall and wrapped by hand with strips of impregnated Madras linen (two and a half inches wide). The strips were applied in the same fashion as a medical nurse

would apply a dressing to a wound so that every next turn lapped over the one below for half of its width and ran in the opposite direction. The impregnating compound was prepared so that it would not get solid when cold. As Dr. O'Shaughnessy, Director of the East India Company's Telegraphs and head of the project, believed, the four-ply insulation thus produced could keep out both water and dirt and protect the wire against worms and insects. Twenty Indians could insulate a mere six hundred metres of rods a day! That was a snail's pace, indeed, especially compared with what present-day machines can do.

The rods were welded end to end so as to form strings each sixty metres long, and the strings were then assembled into bundles of ten strings each, to be finally carried to the site on elephants. For protection against mechanical damage, the bundles were laid in a trough made up of clay tile the shape of a half-cylinder, and covered with another tile, thus making a wireway. After the conductors were laid in the wireway, it was filled with a mixture of three parts by weight of sand and one part by weight of wood tar. The sand was thoroughly cleaned to remove dirt, washed to remove clay and salts, finally dried on an iron pan over the flame of a camp-fire, and mixed with wood tar in an iron kettle heated also by a camp-fire. As the wood tar melted, the mixture was stirred, dipped out with a long-handled scoop, and poured into holes in the tile wireway. After pouring and cooling, the trench was filled up with clay, tamped down, and levelled off.

A gang of fifty workers could lay 300 to 510 metres of line a day. The project was started on November 5, 1851 and completed on February 7, 1852. Three months – fifty men – twenty five kilometres of line. This works out to an average of eight kilometres per month! Here, too, present-day machinery moves a lot faster.

But to go back to Yacobi. When, after his first two short

lines, he got down to building, in 1843, a twenty-five-kilometre underground line, Yacobi had realized that glass tubes were no good. On the other hand, he had noticed that the rubber couplers used on the 1842 line were well preserved. This observation prompted him to have the copper wires for the new line wrapped with two plies of narrow rubber tape. The rubber-insulated wires were buried about a half-metre into the ground without any further protection.

In fact, Yacobi used an insulated, but 'unprotected' wire, and it turned out, as one should have expected, unreliable. Yacobi admitted that himself: "The tests carried out on the Czar Village telegraph line have shown that, when buried in the ground, rubber-insulated conductors suffer from major limitations. Therefore, as a way of protecting them against damage, I feel it necessary to lay them in closed, well-tarred wooden conduits. Also, I believe it will suffice to bury the wooden conduits to a depth of about twelve inches all along the route". He proposed this in 1846 in an explanatory note to the plans of a new thirty-kilometre line that was to be built between St. Petersburg and Peterhoff.

More than a century later, as the newspaper *Evening Leningrad* reported on November 27, 1949, a wooden conduit was found during an excavation near Moscow Station in Leningrad. The conduit lay at a depth of eighty-five centimetres and enclosed glass tubes and insulated wire. That's how our contemporaries got an idea about Yacobi's line.

As this had occurred to Schilling, Yacobi realized before long that underground wire lines were imperfect and, in consequence, short-lived. Although he was aware of the shortcomings inherent in overhead lines, Yacobi was sure they were the design of choice as things stood at that time. Quite logically, he publicly abandoned the idea of 'underground wires' and offered his services in the construction of an overhead telegraph line along the St. Petersburg-Moscow

Railway. But the government officials in charge of the project granted the contract to the German firm of Siemens and Halske which installed, instead, an underground telegraph line 651 kilometres long, using wires insulated with gutta-percha, a rubber-like substance made from the juice of various Malayan trees. In less than two years, the line was removed from service because the insulation was damaged quite often and the faulty spots were extremely difficult to locate. The Treasury had suffered a loss of several hundred thousand roubles. In 1853-1856, the underground line was replaced with one made up of bare conductors strung on poles. As Yacobi wrote in 1857, "It is strange that, in spite of my warnings, the construction of the underground line in Moscow was started when similar lines built in Prussia had proved so poor in service that a decision was taken to abandon the idea entirely. The sole consolation was found, though, in holding mice liable for the damage. It had apparently been presumed that these rodents attacking not only the gutta-percha insulation but the copper wire as well, were either non-existent in Russia or had entirely different tastes."

That's how cable lost its first struggle for survival. But it did so only temporarily and not completely. It may sound paradoxically, but cable was finally able to defend its foothold in water and not on land.

Chapter Four

The Cable Goes Aquatic

WHAT DO WE KNOW ABOUT GUTTA-PERCHA?

As in other countries, the present generation of Russians knows about gutta-percha very little, if anything. Except, probably, a very sad story, "The Gutta-Percha Boy", by the Russian author D. Grigorovich, where a circus boy plunges to his tragic death while doing his number. The story goes nearly a century back, the time when gutta-percha had its hayday, we might say.

In 1735, the Paris Academy of Sciences sent an expedition to South America to measure the arc of the meridian. One of its members, the geographer Charles Condamine, a courageous, persevering and inquisitive man, explored the plant life in nearly all of the Amazon valley. While taking notes of the everyday life of Brazilian Indians, he noticed the milky sap the natives produced by tapping tall, spotty trees which could be seen everywhere on the banks of the river Amazon. The Indians applied the sap to their boats to make them waterproof, made it into bottles, and cast into heavy but springy balls. The sap would thicken and darken in the air very quickly, turning into solid resin-like lumps. The natives called the sap 'caou-tchouc' which was the Indian for 'tree tears'. Condamine gathered a large collection of 'tree tears' and presented it to the Academy. With time, *caou-tchouc* or, more commonly, India rubber, made its appearance in Europe as ready-made products, such as galoshes, or rubber overshoes worn in wet weather (and often simply called 'rubbers'), bottles, and erasers to rub out pencil marks (and often simply called 'rubbers', too). But nobody seemed to know how the milky sap could be carried from Brazil in its native state. This

went on until in 1819 the Scotch chemist Charles Mackintosh dissolved the sap in naphtha obtained at that time as coal-tar was processed into lighting gas. As the story goes, Mackintosh stumbled into his discovery by chance when had mistaken a jar holding naphtha, an oily substance, for the one he actually needed. It may have happened that way, but the unexpected discovery completed the chain of purposeful searches for the solvents of India rubber the chemists had been looking for. Before long, other solvents of raw rubber were also found, among them turpentine. Hardened after its voyage from Brazil, raw rubber could be dissolved to a liquid which was then used to treat fabrics so as to make them water-proof.

Electricians, too, took interest in the new material. Schilling used the rubber sap to impregnate and smear fibrous insulation, and Yacobi used rubber tape to wrap wire. But the users gradually realized that the raw rubber could not stand up to sudden changes in temperature. Even at a few degrees below zero, it would harden, while at only a few degrees above room temperature it would become viscid, all but melt away, and the insulation would let moisture pass through. At the last moment, when, it seemed, the 'caou-tchouc age' was about to end in infamy, when newspapers vied with one another for the coverage of what they named 'the rubber fraud', 'the rubber flop' and 'the rubber fizzle', and raw rubber was about to come off the stage for ever, it was saved by the American inventor Charles Goodyear (1800-1860). He, too, did this by chance. Absorbed in hundreds or even thousands of experiments which had been going on for many years, he put, quite absent-mindedly, a slice of raw rubber liberally sprinkled with sulphur on the top of a hot stove. Instead of melting away, the slice turned into a dry, elastic substance. That's how he discovered, in 1840, a method for hardening raw rubber by means of sulphur, now commonly called vulcanization.

In the meantime, engineers had found that the gums tapped

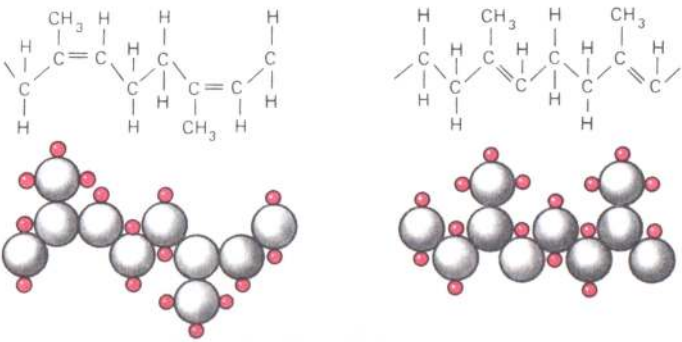


Fig. 4.1. Molecules of natural rubber and gutta-percha

from different tropical trees were as different. The sap from the trees called *Hevea brasiliensis*, came to be known as natural rubber. The gum from a tree that the natives in Singapore and the Malaysian Archipelago call 'isonandra-gutta' and 'isonandra-percha' was named 'gutta-percha'. In fact, the two are relatives or, as chemists say, isomers. Both are high polymers of isoprene, C_5H_8, and they have the same chemical formula. But the methyl groups, CH_3, in the two isomers are located differently: in gutta-percha they are found on one side of the main chain, and in hevea rubber on either side. In contrast to hevea rubber, gutta-percha softens when heated to 55-60°C and becomes as malleable as putty, but not so sticky. On cooling, it hardens without turning brittle, and retains the shape it is given while hot.

The special traits of gutta-percha were turned to advantage in processing. In Europe, it drew attention in 1843. It was made into dolls, "chamber utensils for use in mental homes", chess pieces, ear-trumpets, and flexible 'speaking tubes'. It wasn't unusual at that time to run in a newspaper into an ad item like this: "Small and cheap, Railway Conversation Tubes

Fig. 4.2. Werner von Siemens, one of the founders of cable technology

enable parties to converse with ease and pleasure, whilst travelling, notwithstanding the noise of the train. This can be done in so soft a voice as not to be overheard even by a fellow-traveller. They are portable, will coil up so as to be placed inside the hat".

The first to propose the use of gutta-percha as insulation for underground telegraph lines was Werner von

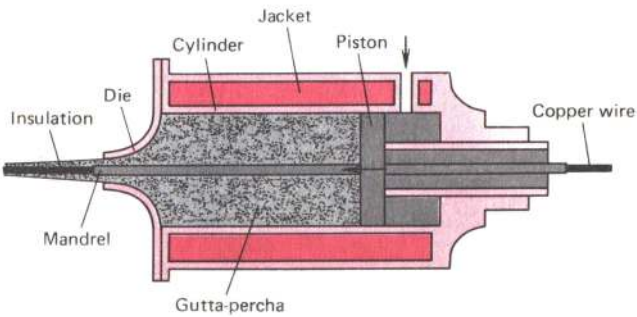


Fig. 4.3. The first press used to extrude gutta-percha insulation over wire

Siemens (1816-1892), a celebrated German electrician and inventor who did much in the field of electrical machines, electrical instruments, and cables. In recognition of his services, he was elected to the Berlin Academy of Sciences and his name has been given to the unit of electrical conductivity.

In 1847, Siemens devised a sheathing press which could apply gutta-percha insulation to wire. The press was simple in design. Gutta-percha was loaded into a cylinder heated with hot water circulating in its jacket. Moving to and fro inside the cylinder was a hollow piston. In fact, the piston moved over a mandrel which was a stationary and likewise hollow tube. The wire to be insulated was let through the mandrel, and the insulation was squeezed over the wire as a jacket through the annular clearance between the mandrel and the die.

Gutta-percha immediately caught Yacobi's attention when he was looking for a good and reliable insulating material. As he wrote, "Almost utterly embittered, I jumped at the idea of using this new material as soon as it made its appearance on our market".

In 1850, Siemens invented a new technique for drawing the

cable core into lead pipes. That's how he described his invention: "If lead pipes are fabricated accurately, it would be an easy matter to force a hemp cord through them with the aid of an air blower, and then, using the cord, to pull through a guttapercha-insulated wire. Then the pipe would be passed through a steel die so as to make it enclose the insulated wire tightly".

By Siemens' method, wire or, rather, several wires stranded together were drawn into lead pipes fifteen metres long each. The job was done manually by a gang of several workmen. Although primitive, the method was revived a century later when aluminium came to be used instead of lead as the outer sheath for cables. Now the cable core was pulled inside an aluminium pipe by machine rather than by hand, but as before the pipe was passed through a die to make it fit tightly to the cable.

Of course, lead-sheathed cables could be fabricated by this process on a limited scale only, mainly for use in railway tunnels. But again, when laid in the ground not protected by a lead sheath, guttapercha-insulated wires proved a failure. Before long it was found that, when exposed to atmospheric oxygen and changes in temperature, gutta-percha would readily be oxidized, dry out (or age, as is customary to say today), and lose all of its physical and insulating properties. On the merit side, it was found that, when immersed in water, gutta-percha would behave well and retain its valuable properties for a long time.

How was it that gutta-percha went aquatic? Overhead telegraph lines were set up with a growing assurance on land. We stress it – on land. But their builders were hard put each time they faced a river, a canal, or a lake. When a need arose to make a crossing, they built, at first, tall masts, but it was soon realized that the method was difficult to implement and unreliable. Finally, attempts were made in the 1840s to lay

guttapercha-insulated wires, both single and twisted together, on the bottom of several rivers and lakes. Gutta-percha passed the test unhurt. There was no need for a lead sheath. But there was danger of another kind that river cables faced – mechanical injury by anchors, bottom ice, and the like. To avoid damage, an iron chain or wire rope was laid on either side of a cable at the bottom of a river or lake. An attempt was made to use heavy iron wires (up to ten millimetres in diameter) along the cable and tie them together with a single iron wire applied in a spiral. The main thing was that the gutta-percha insulation had proved reliable in river water even when it was not protected against moisture. What about seawater?

THE FIRST SUBMARINE CABLE

The question we put above was of particular concern to England and France. Although the telegraph had been ten years old already, the two countries separated by the English Channel a few dozen kilometres wide had no electric communication between them and had to be content with postal services. The semaphore telegraph could not be used because the largest distance that could be spanned between two adjacent semaphore stations was not more than ten to twelve kilometres. On the other hand, the explosive growth of industry and the impressive expansion of commerce in the mid-nineteenth century made it an urgent necessity to have a fast and reliable means of communication between countries as well.

In fact, the scheme for a cross-Channel telegraph was put forward as early as 1849. Its originators were two Englishmen, the Brett brothers: John Watkins Brett, a retired antique dealer, and Jackob Brett, a telegraph engineer. The project was funded by the French government, while the British government and business circles cautiously took up a 'wait-and-see'

stand. The two brothers formed between them a grandiloquently titled "General Oceanic and Subterranean Electric Printing Telegraph Company", and awarded a contract to fabricate the cable they needed to a British firm, "The Gutta-Percha Company" at Newcastle, which had had some previous experience with the manufacture of underground cables. There was no factory in France yet that would be able to cope with an order as big as that. Fabricated purely by a rule of thumb (for nobody knew how to design a cable at that time), the cable was, by our standards, very primitive. It was nothing more than a single copper wire two millimetres in diameter surrounded by a coat of gutta-percha five and a half millimetres thick for insulation to an outside diameter of thirteen millimetres – less than your little finger. The cable was coiled on a wooden drum seven feet in diameter and fifteen feet long. The drum could accommodate forty-five kilometres of cable and tipped the scales at six tons.

The cable drum was set up on the after-deck of the *Goliath*, a small steam tug, so that it was free to rotate on a metal axle held between posts. Another steamer marked out the route for the cable line with buoys and flags. In the morning of August 28, 1850, the *Goliath* started the cable-laying operation at Cape Southerland, five kilometres north-east of the English seaport of Dover. That was a slow job, with the *Goliath* having to stop every 100 metres or so in order to attach ten-kilogram lead weights to the cable – without them it would not sink to the bottom properly because the weight of the cable turned out to be equal to the weight of the water it displaced. The lead weights added over two-thirds to the cable's weight. All in all, the cable-laying party went on at a pace of six or seven kilometres an hour.

The same evening, after an uneventful crossing, the cable was safely landed on the French coast near Cape Gris-Nez, twenty kilometres south-west of the French seaport of Calais.

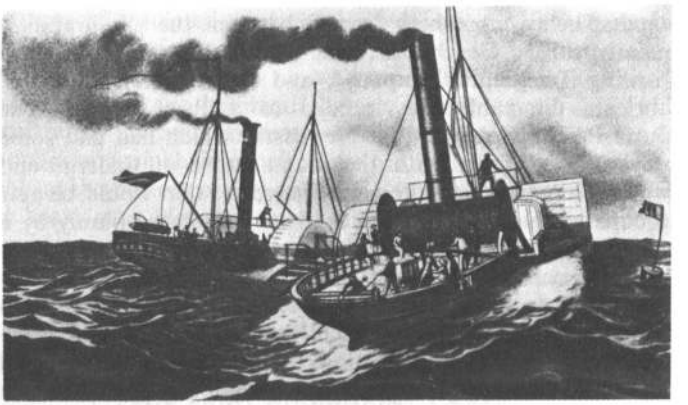


Fig. 4.4. *Goliath* laying the first submarine cable across the Strait of Dover in 1850

Unfortunately, the signals transmitted from the English side emerged on the French side as a mass of jumbled characters which made no sense whatsoever. Only once some words got through without mutilation. Anyhow, it was the first message, or cablegram, to have been sent over the first submarine cable. It was the first and the last, though. The trouble was that nobody had yet learned to design properly either the cable itself or the conditions to be maintained during transmission. Today we are in a position to say that the cable had a prohibitively high resistance to direct current and a prohibitively large electric capacitance. On top of that, a fisherman fouled the slim cable inadvertently with his trawl off the French coast the next day. Since the line was so light he was able to haul it aboard. When he saw the glint of the copper against the dark background of the gutta-percha insulation, the fisherman thought it might be gold, and cut out a nice piece of cable. The incident has since become a reading-book

item, and every writer of the history of electric communications makes it a point to mention the ill-fated fisherman.

That was an infamous end for the first submarine cable. Importantly, it had only one conductor, and the return path for the telegraph circuit was provided by seawater whose conductivity is 100 to 1000 times that of earth and fresh water. Despite its failure, however, the project had come as a proof that submarine cables could be used for electric telegraphy.

People at that time had no idea about communication cables. As an old joke goes, one gentleman, seeing the cable set up ready for laying, declared roundly: "The people in charge of the job must be fools: how could you possibly drag the cord that long and heavy and over the rough bed of the Channel". The gentleman was under the impression that the cable was to be jerked the same way he used a bell-cord to summon his domestics at his mansion.

The next year a new cable was made, altogether different from its predecessor. It consisted of four copper wires each one and a half millimetres in diameter and each separately covered with two layers of gutta-percha two and a half millimetres thick. The wires were stranded by a machine borrowed from rope manufacture. (The first stranding machines of the cage type appeared in 1837). The stranded core was covered with tarred hemp two millimetres thick and on top of that – and most importantly – the cable had a protective armour. The ingenious originator of the idea has remained unknown but he could have reasoned as follows: "Since river cables are protected against mechanical damage with iron wire ropes placed on either side, a better job could be done by placing the cable inside".

That's how, in 1850, an armour was invented for submarine cables, made up of iron wires galvanized to avoid corrosion. That was the armour which was to remain an integral part of any underwater cable – river, submarine, or transoceanic – for a

hundred years. Over its hemp wrapping, the 1851 cable had ten galvanized iron wires seven millimetres in diameter. They were laid to form a spiral (as in a steel wire rope), touching one another in a single layer, thus making up a continuous protective cover. The outside diameter of the cable was thirty-five millimetres, and its weight per metre run was more than thirty times that of its predecessor. Obviously, no lead weights were needed to lay it in the sea. Drawn to the same scale, cross-sections of the 1850 and 1851 cables are shown in Figure 4.5. Of course, this is only a sketch. Actually, the stranded conductors and the armour wires were ovals, rather than circles, in section.

The 1851 cable was very near a true cable even by present-day standards. It had a conductive core, a core insulation, an armour. You may ask, though: And where was the sheath? The point is that an underwater cable using an insulation able to stand up well to the action of water (such as the gutta-percha insulation of the nineteenth century or the polyethylene insulation of the latter half of the twentieth century), needs no sheath to protect it against exposure to the environment. In the 1851 cable, the armour actually doubled as a sheath.

The second submarine cable was laid at a depth of about fifty metres between Dover on the English coast and Sangat on the French coast, a little village eight or nine kilometres south-west of Calais, on September 25, 1851. After a few weeks of testing, the line was turned over for service. Incidentally, the same route has recently been chosen for the under-Channel tunnel to be built jointly by Britain and France.

At first, it took anywhere from half an hour to an hour to transmit a single message between Paris and London. A whole year had passed before the operators dared to connect the submarine cable to the overhead line for lack of an understanding of how electric current could pass from one to the

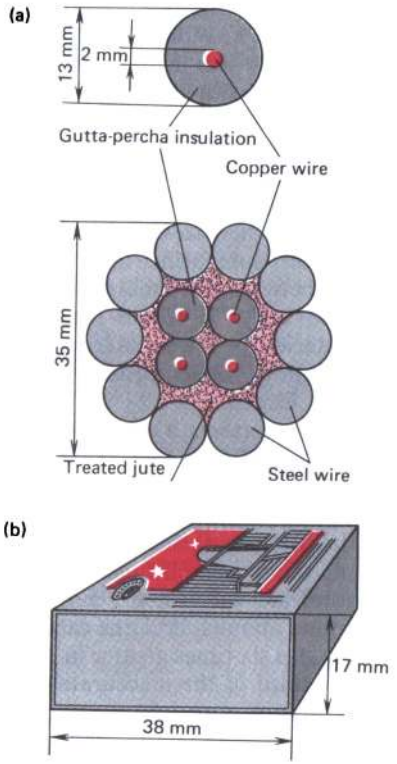


Fig. 4.5. Early submarine cables: (*a*) 1850 and (*b*) 1851

other. On its way from London to Paris, every message had to be re-transmitted twice: first at Dover and then at Calais. It was not until November 1, 1852 that a direct connection was set up between the two capitals.

The success of the new submarine telegraph line started a boom in cable manufacture. Within the next two years the Gutta-Percha Company, which had a virtual monopoly of core insulation, supplied over two and a half thousand kilometres of covered wire to the manufacturers who provided the protective armouring – more than had been fabricated in all of the previous decade.

In 1852-1854, submarine lines were laid first from England to Ireland and Belgium, then to Germany and the Netherlands. In 1854, further submarine lines were laid in the Mediterranean – first between Sardinia and Corsica, and then between Corsica and Italy. It would seem there were no insurmountable obstacles for the submarine telegraph. Before long the most ambitious men turned their thoughts to spanning the Atlantic Ocean.

Before going on any further, a few points seem to need clearing up. As noted earlier in this book, communication cable has not been very lucky in popular writings. Little has been written about it, and then not very accurately. To believe one such source, the first submarine cable was a quarter of a centimetre thick, and the second, around twelve centimetres in diameter. Both figures are wide off the mark and show how little their source knows about submarine cables. Actually, the first submarine cable was six times greater in diameter, and the second less than one third of the inaccurately quoted size, as can clearly be seen from Figure 4.5.

Another source likens the 1851 armoured cable to a heavy steel wire hawser plaited of many wires and given several coats of insulation. That is a funny description, to say the least, because the things were arranged exactly the other way around. Still another source believes the galvanized armour wires were the cable's conductors.

THE BATTLE OF THE ATLANTIC

Rather, it was a battle against the Atlantic.

The laying of the first telegraph cable across the Atlantic may, in a way, be likened to the voyages of Christopher Columbus to America. Of course, the resemblance, if there is any, is only an outward one, and this author is far from any desire to apply the same yardstick to the two events. Still, Columbus spent a decade in his voyages – from 1492 to 1502. The Atlantic project, too, took a decade to complete – from 1857 to 1866. Columbus made four voyages to the American continent. It took the effort of five expeditions to lay the cable that finally linked Europe and America. Dramatic situations were many in both cases, except that the men in the nineteenth century didn't threaten to hang their admiral. Lastly, Columbus discovered America. The cable united Europe and America, figuratively speaking.

How urgent it was in the mid-nineteenth century to install a telegraph line between the Old and New Worlds can be realized from Table 3 which gives the time it took for a ship to cross the Atlantic and carry mail.

The table gives the 'personal bests'. On the average, a message would usually travel for at least three weeks across

Table 3. Sailing Time between Europe and America

Steamship	Year	Days in voyage
Savannah	1819	26
Sirius	1838	19
Great Western	1838	16
Great Eastern	1860	11

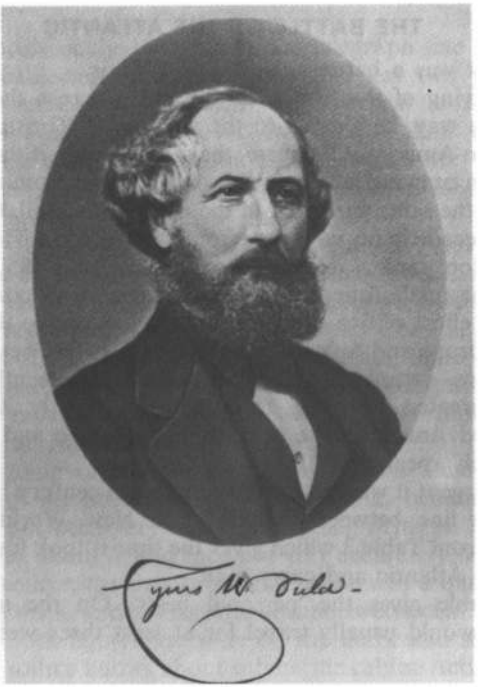


Fig. 4.6. Cyrus Field, the mastermind behind the first Atlantic telegraph cable project

the Atlantic before it reached its destination. As a rule, ships sailing for Europe would first call at Newfoundland to take more coal and fresh water and do minor repairs, spend a few days there, and then resume their voyage to New York.

In 1853, the English engineer F. N. Gisborn was engaged in building a telegraph line between New York and St. John's, the capital of Newfoundland and the nearest port of America

to the continent of Europe. The project was to be an over 1500-kilometre line using mostly overhead conductors strung on poles, and underwater cables where it was to cross the numerous straits. Steamers carrying the mail from Europe would call at St. John's and any urgent messages could be flashed along the telegraph to New York at once, thus saving a few days. Because of the extremely adverse climate and the wild nature of the country, however, the project failed. The company set up to build it went bankrupt, and Gisborn who had been left holding the company's debts had to go to New York in an attempt to raise more money for the scheme. There, by good fortune, he met Cyrus West Field, a businessman.

Field was neither a scientist nor an engineer. Nor was he keen on telegraphy. But he deserves every word written about him in books on the history of electric communications. He had a knack of making things go, was broad-minded, and could see everything in a true perspective. He had listened to what Gisborn had to tell him and said: "Your project is no good. If you can't lay a wire from Cape Ray, Newfoundland to Valentia Bay, Ireland, nobody will need your preposterous steamship line. If, on the other hand, you can do that great job, your scheme will make no sense either, for nothing would then stand in the way of laying the line from Europe to America directly".

As we will see later, Field was too categorical in his negative view of Gisborn's project, but he was right in summing up 'the great scheme'–"Put a telegraph cable across the Atlantic". Soon, backed by other far-sighted men, Field set up what they called the "New York, Newfoundland and London Telegraph Company" which lost no time in getting down to brass tacks. The mammoth size of the scheme can be seen from two figures: they were to lay about four thousand kilometres of cable on the ocean floor at depths as low as four and a half kilometres.

Some thirty years ago, on hearing about transoceanic cables,

the laymen would ask with distrust: "Is it true that the cable is laid right on the ocean floor and is not let floating in the water?" A layman's distrust is forgivable, especially if we recall how some self-styled inventors proposed to hold the cable floating deep in the ocean on air-filled baloons. Specialists, too, doubted if electric current could propagate over the wires spanning so huge a distance. To dispel all fears and doubts, an experimental overhead line was set up in the United States, running for over three thousand kilometres from New York through Charleston and Savannah to New Orlean. In Britain, too, the wires of all the principal telegraph lines, including those in Ireland, were hooked up into a single circuit on the night of October 9, 1856, as a replica of the proposed Atlantic cable. This circuit, made up mostly of overhead lines and partly of underground and submarine cables, totalled eight thousand kilometres in length. Signals went through the circuit as well as they did in the American test. It is not unlikely that nineteenth-century electricians with their discoveries and triumphs might seem primitive to their twentieth century counterparts overloaded with the latest knowledge, and even schoolboys in a senior grade today would say at once that electric signals 'whisked' through what people in the nineteenth century thought to be a 'superline' in less than 0.03 s. Nevertheless, a big triumph it was.

In 1856, the New York-Newfoundland part of the line, built in two and a half years, did go into operation. After all, Gisborn's project had proved viable. It was time to come to grips with the Atlantic.

The five attempts to lay the first transoceanic cable have been described in detail in several books. A most entertaining story has been told by Arthur Clarke, a science-fiction writer of world renown, in his "Voice Across the Sea".

While keeping in view the highlights of the ten-year effort,

we will place emphasis on its 'cable' aspects. To make the four thousand kilometres of cable (with a good margin to accommodate the hills and valleys of the oceanic floor along the route), close on thirty thousand kilometres of copper and over five hundred thousand kilometres of steel had had to be drawn and spinned into wire. Those keen to compare things might say this wire would be enough to string a line from Earth to the Moon and to go a third of the way back, or to girdle the globe thirteen times around. Why so much wire was needed for the line can be learned from Table 4.

The conductor consisted of seven strands of copper wire, and not of one, twisted together and insulated by three thin coats of gutta-percha. The insulated core was made in delivery lengths of two miles and wound on drums. Then it was put to a double test in which the electric resistance of the conductor and of its insulation was measured. Thus tested, the delivery lengths were joined together – the ends of the seven strands were scarfed, put together, and soldered with silver. The gutta-percha insulation was glued together, and the joints were wrapped with gutta-percha tape. The insulated core was then covered with a layer of hemp which in turn was armoured. The armour's make-up was anything but simple, too. At first, seven wires were twisted into a strand, then 18 such strands were applied over a bedding of treated jute.

The entire cable was made in the short time of six months, which works out to an average of about 700 kilometres a month – a rate which has seldom been matched since. The conductors were insulated by the Gutta-Percha Company, and the armour was made by two other companies. Silly things happened, too. Since the armour was made by two different companies, the steel wires were applied to the two halves of the cable in opposite directions. Because the reaction of the armour spiral would cause the cable to spin about its axis in

the opposite direction to the lay of the armour wires, the cable might break during the laying operation at the point where the two halves of armour met.

In spite of all troubles and distractions, the cable had been made by July 1857.

It would be naive to think that the cable project had only well-wishers and proponents. As one sceptic said, "It was a mathematical impossibility to submerge the cable at so great a depth, and if it were possible, no signals could be transmitted through so great a length...".*

The cable-laying expedition set out to work from the small Valentia Bay near the south-western tip of Ireland on August 6, 1857. Two warships had been adapted to cable laying. They were the *Niagara*, the world's largest steam frigate, and the *Agamemnon*, a British jury-rigged and screw-driven warship. That was a re-appearance of the name of Agamemnon, and it has firmly gone down into the history of communications on our planet. A greater part of the cable, some two thousand tons, was loaded on board the *Niagara* whose displacement was 5200 tons, and the remainder on board the *Agamemnon* whose displacement was 3200 tons. The ships' holds had been enlarged into huge circular wells or tanks, winches were set up at the sterns to pay out the cable gradually into the water, slipways were installed to ease its descent, and dozens of tension and braking devices were provided.

The *Niagara* was leading the expedition at a pace of two to four knots. That was as many nautical miles, or 3.7 to 7.5 kilometres an hour. All went well and the *Niagara* kept up communication with the land over the cable she was laying until a catastrophe occurred: by an unfortunate error the brake on the paying-out mechanism was applied too fast, and the cable snapped – 355 nautical miles' length of cable (620

* Clarke, Arthur C. *Voice Across the Sea.* London, F. Muller, 1958.

kilometres) was left lying at a depth of two nautical miles. There was nothing to do but to postpone the attempt until the next year. The first attempt had ended in a failure. After a week at sea, the expedition turned home empty-handed. No, not empty-handed – they had learned a good lesson and had proved that a deep-sea cable could be both laid and operated. The result was worth while the effort.

The next two attempts were made in the summer of 1858. In the meantime, a new supply of cable had been procured and the paying-out mechanism which had been the prime cause of the failure was completely re-designed – a new type of friction brake was used which would automatically release if too much tension was applied. This time it was decided to start from mid-Atlantic and let the ships lay the cable in opposite directions. A test had first been run in the Bay of Biscay, in which the crews were put to a drill in laying the cable from the two ships at the same time and in splicing the two halves afloat. A trial laying was carried out, with the cable laid at a depth of six thousand metres, and proved successful. Huge buoys were also tried in order to mark breakage points.

The second expedition began on June 26, 1858 and went on for only three or four days. In those days, the cable snapped three times: at first on the *Niagara* after she had laid just a few kilometres of cable, then on the *Agamemnon* when the ships were already 150 kilometres apart, and finally on both ships after 370 kilometres of cable had been laid. Shortly before, the ships had had to ride out one of the worst Atlantic storms ever recorded, the supplies of food and fresh water were running low, and the captains ordered to head back for England. However, the new failure didn't discourage the enthusiasts. In about a month, on July 29, 1858, the *Niagara* and the *Agamemnon* arrived at their rendezvous point in mid-Atlantic, spliced the cable, weighted it with a piece of lead, sent it

overboard, and parted to sail their opposite courses on the fourth try.

Although not without minor mishaps, the operation went on non-stop for a whole week. On the Thursday morning of August 5, 1858, the *Agamemnon* entered Dowlas Bay, Valentia, Ireland, and the *Niagara* went into anchor in Trinity Bay, on the eastern coast of Newfoundland. The submarine cable line 3800 kilometres long had been completed. Ten days later, on August 14, Queen Victoria of England sent the first cablegram with her greetings to James Buchanan, the fifteenth president of the United States. At last, the electric telegraph had linked Europe to America.

A wave of celebrations swept the United States and England. Newspapers were lavish in their praises. Even the conservative *Times*, not prone to hyperbole, informed its readers: "The Atlantic is dried up, and we become in reality as well as in wish one country...". Samuel F. B. Morse called the event the greatest feat of the century.

As Stephan Zweig wrote later: "That was an unheard-of victory: for the first time since intelligence dawned upon the Earth, a thought was able to cróss the Atlantic at the velocity of thought".

However, the triumph was short-lived: two weeks later it was wiped out by bad news. On August 31, New York was still engrossed in a feast in honour of Cyrus Field (even a piece of cable was carried through the city for everyone to see), but on September 1 the apparatus failed to receive a single intelligible word from across the ocean. Extremely erratic during the two weeks, the line had now completely gone out of action and had practically ceased to exist.

During its two weeks of operation the line, which had flashed up as a firework and fizzled out so suddenly, transmitted a total of four hundred cablegrams carrying between them 4360 words. After their brief union the continents were

once more as far apart as ever. Why was it that the cable had failed? In all probability, its insulation was broken down by an excessive voltage – the supply source set up on the shore delivered two thousand volts. The voltage was raised so high in order to boost the signals. Otherwise, the receivers weren't able to record them because of a very low sensitivity and the huge distance involved.

THE LORD OF CABLES

It was not until eight long years later that the hope became a reality. The eight years were filled with persistent search, with difficulties which were to be overcome and problems to be resolved, with rewarding discoveries and frustrating failures, with risky but ingenious decisions, with dramatic and, sometimes, funny events. They were the years that had finally led to a victory.

It took nearly a year for a special Joint Committee to carry out an inquiry into the cause (or, rather, causes) of the failure suffered by the Atlantic line and, later, by another undersea cable line 2250 kilometres long, laid through the Red Sea and the Persian Gulf to serve as the closing link in the telegraph chain from Britain to India. The failures were mainly ascribed to bad design, workmanship and materials, and lack of experience and satisfactory facilities for cable-laying operations. To this we may well add the low standards of electrical engineering at that time. This point was forcefully stressed by one of the witnesses before the committee: "It's a great pity that those who touch upon the question do not make themselves familiar with the laws of Ohm, it would set aside all those absurd discussions that take place".

There was, of course, a silver lining to the cloud of failures – a wealth of new experience in cable design, manufacture and testing, a wider knowledge of cable materials, and

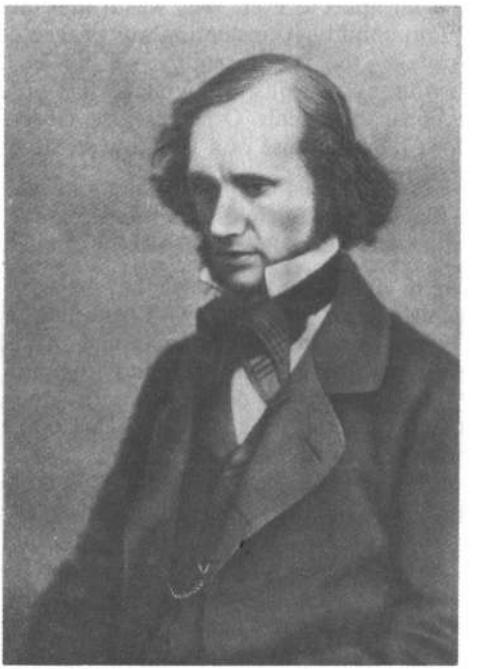


Fig. 4.7. William Thomson, Lord Kelvin of Largs

better skills in splicing cable lengths. In the meantime, over 30 thousand kilometres of cable had been manufactured for seventy-five submarine lines, and a 1500-kilometre cable line had been laid in the Mediterranean to join Malta and Alexandria.

The best scientists and engineers were invited to draw up specifications for the new cable, among them Professor Charles Wheatstone, the brothers Werner and Wilhelm Siemens, and

Latimer Clark. The life of the team was the famous William Thomson (1824-1907), the chief consultant on electric matters to the first cable-laying expeditions. Among the most eminent scientists of the nineteenth century, Thomson made himself known in many fields of theoretical physics and engineering, and his work laid the foundations for modern thermodynamics. He also made valuable contributions to mathematics, hydrodynamics and electrical engineering. He introduced the concept of absolute temperature, formulated the basic theory of electric oscillations, and invented quite a number of scientific instruments, including an electrometer and a sensitive galvanometer. His best-known work was the invention, in 1870, of the siphon recorder for the Atlantic cable. On the completion of the Atlantic Cable in 1866 he was knighted, and was later raised – first among all scientists in Britain – to the peerage in 1892 to become Lord Kelvin of Largs. His new name was later given to a temperature scale (the Kelvin scale) and to the unit of thermodynamic temperature in the International System of Units – the kelvin (K).

Back in 1854, Thomson set out to learn how fast an electric signal made up of dots and dashes could travel down a cable and be picked by a receiver.

It is a common error to think that electricity travels in a cable at the speed of light, that is, 300 thousand kilometres a second. Actually, its speed depends on the frequency of the current and the properties of the cable itself. These properties are often called 'electric characteristics' or, more specifically, 'transmission constants'. They include above all electric resistance and electric capacitance.

The resistance of a conductor depends on its material, its length l, its cross-sectional area S, and temperature. The unit of electric resistance is the ohm, Ω, after Georg Simon Ohm (1787-1854), the eminent German physicist who discovered the mathematical theory of the electric current, known as Ohm's

Law. The resistance of a cylindrical conductor at a temperature of + 20°C is

$$R_{cond} = \rho l/S = \rho 4l/\pi d_0^2$$

Here, ρ is the resistivity of the material. If we express l in metres and S in square metres, the resistivity will have the units of ohms m (Ω m). However, a cable is a very long conductor, and it is more convenient to state its length in kilometres. On the other hand, its conductors are very slim, so their diameter d_0 is measured in millimetres. Therefore, the resistivity of a cable has the units of ohms mm^2/km. For convenience, it is customary to refer the constants of a cable to unit of length, that is, the kilometre.

Of all metals, silver has the highest electrical conductivity and, therefore, the lowest resistivity

$$\rho_{Ag} = 16\ \Omega\ \text{mm}^2/\text{km}$$

as measured at + 20°C. Copper comes next with

$$\rho_{Cu} = 17\ \Omega\ \text{mm}^2/\text{km}$$

then come gold (with $\rho_{Au} = 24\ \Omega\ \text{mm}^2/\text{km}$) and aluminium (with $\rho_{Al} = 28\ \Omega\ \text{mm}^2/\text{km}$).

The resistance presented by an entire cable or a cable line is

$$R_{cable} = R_{cond} l$$

A single-conductor cable is in effect a tubular capacitor. As will be recalled, a capacitor consists of two conductors, or plates, separated by a layer of dielectric. The key parameter of a capacitor is its capacitance which depends on its geometry, size, shape, and properties of the dielectric. For a flat (parallel-plate) capacitor, the capacitance is

$$C = \varepsilon_r \varepsilon_0 S/a \text{ (farads)}$$

Here

ε_r = relative permittivity of the insulation. This is a dimensionless quantity which has a specific value for

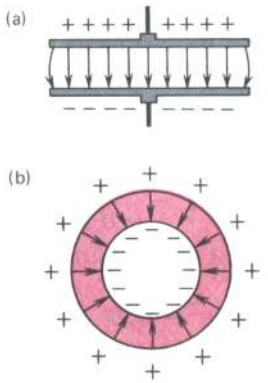


Fig. 4.8. Capacitors: (*a*) flat (parallel-plate) and (*b*) tubular

each insulating material (as is the case with resistivity). For example, air has the lowest value of $\varepsilon_r = 1.006$, polyethylene 2.3, and gutta-percha, 3.5

ε_0 = dielectric constant, or permittivity of vacuum

S = surface area of the capacitor plates

a = spacing between the plates

The unit of capacitance is the farad after Michael Faraday (1791-1867), a highly distinguished English chemist and natural philosopher whose achievements in electricity and magnetism cover the entire field of these sciences. One farad is, however, too large for practical purposes and so use is made of its submultiples: the microfarad (μF) equal to one-millionth of a farad; the nanofarad (nF) equal to one-thousand-millionth of a farad; and the picofarad (pF) equal to one million-millionth of a farad. The capacitance of the globe is a mere 709 microfarads. The capacitance of a cable of length l is

$$C_{cable} = Cl$$

In a single-conductor submarine cable, the inner plate of the equivalent capacitor is the conductor of diameter d_0, and the outer plate is the seawater finding its way to the outer surface of the insulation of diameter D between the wires of the steel armour. Therefore, the capacitance of the single-conductor cable, viewed as a tubular capacitor, per unit length is

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln D/d_0}$$

It remains to add that the dielectric constant, or permittivity of vacuum, ε_0 is

$$\varepsilon_0 = 10^7/4\pi c^2 = 1/(4\pi \times 9 \times 10^9) \text{ F/m}$$

where $c = 3 \times 10^8$ metres per second is the velocity of light in a vacuum.

When the operator at the sending end of a telegraph line presses his key, the current supplied by a battery flows into the cable, but reaches the receiving end with a delay equal to θ. Since the frequency of direct current is zero, this delay is solely decided by the product $C_{cable}R_{cable}$, called the time constant of the cable. In units of time

$$\begin{aligned}\theta &= 0.03C_{cable}R_{cable} \\ &= 0.03ClR_{cond}l \\ &= 0.03CR_{cond}l^2 \text{ seconds}\end{aligned}$$

Direct current propagates in a cable at a relatively low velocity – from eight or ten to forty thousand kilometres per second. Now we can compute the value of θ for the first unfortunate Atlantic cable 3800 kilometres long (its data can be looked up in Table 4):

$$\begin{aligned}\theta &= 0.03 \times 0.15 \times 10^6 \times 6 \times 3800^2 \\ &= 0.4 \text{ second}\end{aligned}$$

Therefore, we may say that the current propagated in that cable at a velocity of 9500 kilometres per second.

Table 4. Vital Statistics of the Atlantic Telegraph Cables Laid in 1857-1858 and 1865-1866

Particulars	Unit	Cable	
		1857-58	1865-66
Number and diameter of copper wires making up the conductor	mm	7 × 0.71	7 × 1.245
Dia. of the conductor	mm	2.15	3.74
Cross-sectional area of the conductor	mm^2	2.8	8.5
Resistance of the conductor	Ω/km	6	2
Plies of gutta-percha insulation	—	3	4*
Insulation thickness	mm	2.8	2.8
Insulated diameter	mm	7.8	9.5
Cable capacitance	F/km	0.15×10^{-6}	0.21×10^{-6}
Thickness of jute bedding	mm	1.7-1.8	2.2-2.3
Number of armour wires or strands	—	18 × (7 × 1)	10**
Armour wire diameter	mm	0.71	2.24
Outside diameter of cable	mm	16	28
Mass of cable	kg/km	500	1000
Weight of cable in air	kN/km	5	10
Weight of cable in water	kN/km	3	3.9
Tensile strength of cable	kN	33	78
Breaking length of cable in water	km	11	20

* Alternated with five plies of Chatterton compound (see below).
** Each armour wire was wrapped with a ply of treated jute about 2.5 mm thick.

In contrast to a short line, the current, i, propagating in a long line cannot reach its steady-state value given by Ohm's law, $I = V/R$, at once. At the end of time interval $\theta = 0.4$ s, it is a mere 0.16 per cent of I. At the end of time 6θ (which in our case is 2.4 seconds), i_6 is half its steady-state value. At the end of time interval 10θ (that is, in 4 seconds), it is eight-tenths of I, and only at the end of time 25θ (in 10 seconds) does it come close enough to its steady value to become equal to $0.994I$. The manner in which the incoming current rises with time is plotted as what is known as the Thomson curve. For the incoming current to be able to reach a desired value and for the cable to be able to discharge after that, the signals should be sent into the line at not too high a rate, or repetition frequency. Failure to do so was responsible for the fact that in the 1858 line signals 'crowded' upon one another, and the transmission was mostly unintelligible.

Telegraphy uses the concept of signalling speed. It tells what time spacing there should be between two consecutive pulses so that each can be received distinctly. It ought not to be confused with the velocity of propagation in a cable. Thomson has shown that the speed with which messages can be sent is inversely proportional to the time constant of a cable:

$$w = k/C_{cable}R_{cable} = k/CR_{cond}l^2$$

where k is a proportionality factor.

It is also seen that the signalling speed decreases with the square of cable length. This relation, known as the Thomson Law of Squares, was neglected in changing over from relatively short undersea to long transoceanic lines. As the equation suggests, the transmission can be speeded up by reducing the product CR, that is, by reducing any of its two factors. If we know the length of a line, l, and the signalling speed to be obtained, we can readily find the required primary constants,

R and C, of the cable, and hence its structural dimensions, d_0 and D.

Of course, what Thomson did was not the first case when a scientific discovery was put to practical engineering purposes, but it was the first in the design and manufacture of cables.

Thomson's contribution to electric telegraphy over underwater cables was not limited to theory. To avoid an excessive increase in signalling voltage, he proposed to use as a receiver the highly sensitive mirror galvanometer he had invented – it was able to sense currents as small as thirty to forty microamperes. Later, four years after the completion of the 1866 Atlantic cable, he invented what he named the siphon recorder, a still more sensitive telegraph receiver. As its name implies, the heart of the device was a siphon – a very fine glass tube bent into a U. One end was dipped in an ink-bottle, and the other was held so that it could draw a continuous line on a moving paper tape. Now the telegraph receiver was sensitive enough to respond to currents as small as twenty microamperes.

Thomson may rightfully be named the founder of design theory for long transmission lines. He derived differential equations defining the voltage and current at any point on a line depending on its primary constants R and C. The equations were later extended to long transmission lines operating on alternating current (such as a. c. power transmission and electric communication lines), often termed distributed-constant (or distributed-parameter) lines, and are known as the telegrapher's equations.

Thomson was the first to propose that the conductor of a cable should be made from wires twisted together so as to improve its flexibility. He was behind many innovations in cable manufacture and a stricter quality control, and insisted that the wires should be made of the purest copper.

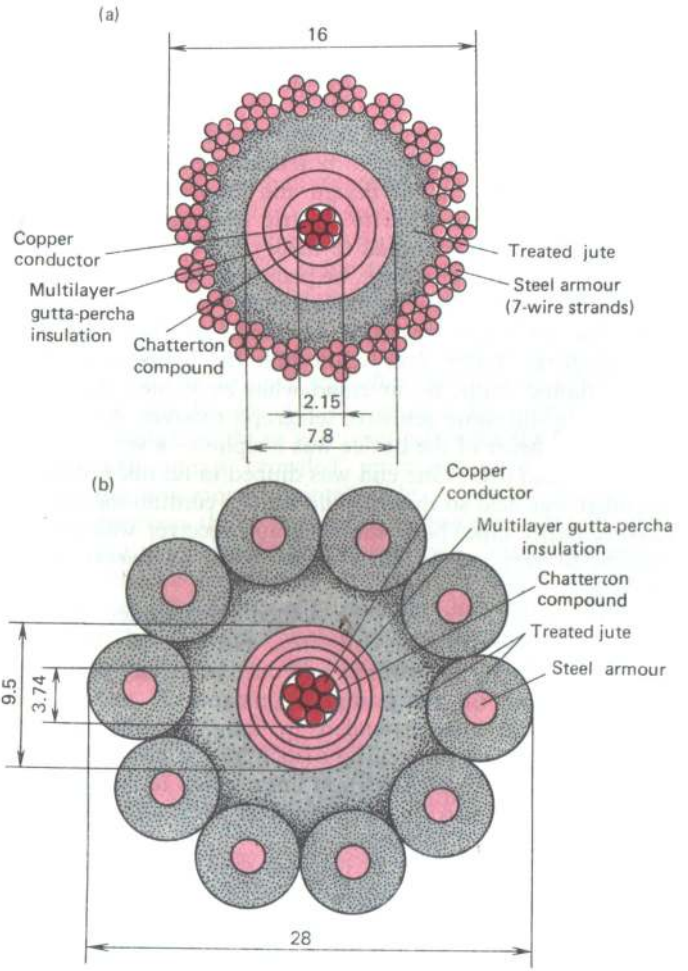


Fig. 4.9. Atlantic cables: (*a*) 1857-1858 and (*b*) 1865-1866

But let us go back to the deep-water cable – the leading character in the Transatlantic epic of the past century. It markedly differed from its predecessors in construction and quality. For one thing, its cross-sectional area was trebled, and this served to reduce the resistance of the conductor to one third of its previous figure. Although there was a small increase in the capacitance, the time constant $C_{cable}R_{cable}$ was reduced by a factor of two and a half. In consequence, there was a proportionate increase in propagation velocity and signalling speed.

Instead of three plies as before, the conductor was insulated with four plies of thin gutta-percha interleaved with Chatterton compound, a mixture of three parts by weight of gutta-percha, one part by weight of resin, and one part by weight of pitch. Thus insulated, the conductor was next wrapped with a ply of tarred jute and encased in an armour made of single steel wires. A new thing about the armour was that each wire was covered with a layer of treated jute about three millimetres thick. This was done mainly in order to reduce the weight of the cable in water (jute has a lower density than water). Although the new cable was twice as heavy in air as its ill-fated predecessor, its weight in water was by a mere third more. Through a sturdier design, the cables laid in 1865 and 1866 were nearly two and a half times stronger than the cables used in 1857 and 1858.

Table 5. Signalling Speed and Propagation Velocity in the Early Atlantic Cable Lines

Year	Line length, km	Travel time of signal, seconds	Propagation velocity, km/s
1858	3800	0.4	9500
1865 and 1866	3500	0.15	23 500

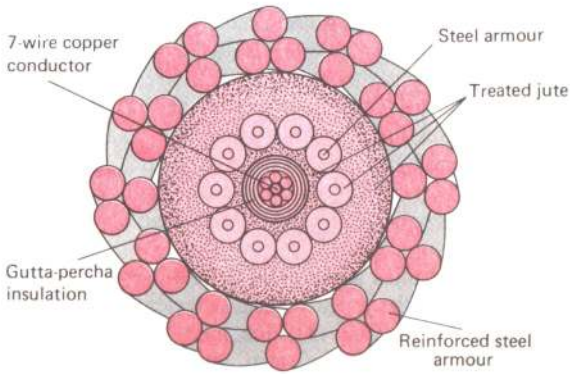


Fig. 4.10. Cross-sectional view of the land leg of the 1865-1866 Atlantic cable

The shore ends of the line were protected from damage through chafing against rock as the water would rise and fall in tides and also from injury that might inadvertently be caused by the anchors of ships. For this purpose, they had a double armour – the armoured cable was enclosed in a bedding of treated jute, and this was covered with a heavier armour which consisted of twelve strands each twisted from three iron wires.

TRIUMPH

As we have seen, a good deal of effort, both scientific and engineering, had been put into the fourth Atlantic cable expedition. Also, its sponsors were lucky to buy for next to nothing the fabulous *Great Eastern*, the largest and among the most beautiful ships in the world at that time. The services this ship did to the Atlantic cable were so important that it

deserves a special mention. It was designed by Isambard Kingdom Brunel (1806-1859), the greatest engineering genius of the Victorian era. He was born in Rouen, France, entered the French Navy, and emigrated to the United States to become the chief engineer of New York. Later, he settled in England and invented many mechanical tools. He also built the Thames tunnel which was begun in 1825 and finished in 1843. On top of that, he built a number of magnificent stone and iron bridges and ports in England and took part in the construction of the first railway telegraph line. He also created several steamships, unique for that time, intended for scheduled services across the Atlantic. They were the *Great Western* (1838), the *Great Britain* (1845) and lastly the *Great Eastern* (1858), the mightiest ship that had ever moved upon the sea.

The *Great Eastern*, a masterpiece of shipbuilding, was a long way ahead of the needs of the time. She started her career on a tragic note: it took eightly-two days to launch her, with grave injuries to several workmen and even a fatal case. When the *Leviathan*, as the ship was christened originally, was just registered at her port on the Thames, her owners went bankrupt. The new owners re-named her, but ill fate wouldn't let go off her. After her maiden voyage in 1859, when the ship was riding at anchor at Hastings, a steam pipe burst open, and several seamen were scalded to death. Her first master drowned soon.

The prejudice against the ship was so strong that when she sailed for New York, a mere forty-six passengers were bold enough to have come along. That was nothing for a ship built to carry four thousand. As Jules Verne wrote, "She was the utmost in perfection. She was not simply a ship but a whole town". She completed the voyage in ten and a half days – an amazing speed for that time. (Nearly a century later, the *United States* made her trip in three and a half days). But when she sailed back, the ship was again empty. At Liverpool, the

bailiff applied a court's seal to the ship and notified the owners that the *Great Eastern* was to be sold by auction.

The *Great Eastern* was a wonder, indeed. She was two hundred and ten metres long and twenty-five metres wide, had a displacement of thirty-two thousand tons, and could carry twenty thousand tons of cargo. Her screw over seven metres in diameter was driven by an engine which developed 1600 horsepower, and her paddle-wheels seven and a half metres in diameter were actuated by engines of 500 horsepower each. Thus propelled, she could sail at twelve to fifteen knots (twenty-two to twenty-eight kilometres an hour). Also the ship's six masts carried sails which totalled between them over five thousand square metres in area. Her crew was four hundred strong. The *Great Eastern* was not exceeded in size until the *Lusitania* was launched in 1906 – forty-eight years later.

A turn for the better, leading the *Great Eastern* to world-wide fame, began on June 24, 1865, when she sailed from the Medway in south-eastern England, south of the Thames's estuary, carrying seven thousand kilometres of cable coiled and stowed away in her holds remodelled into three huge tanks, eight thousand tons of coal, water and provisions for five hundred men.

The fourth Atlantic cable-laying expedition started from Ireland on the evening of July 23, 1865. Before that the cable's shore end fifty-five kilometres long had been laid and spliced with the main cable on board the *Great Eastern*. There were no signs of any impeding disaster.

But as fate would have it, signals came – at first on the second and then on the seventh day – there was something wrong with the insulation. There was nothing to do but to haul the several kilometres of cable aboard – and this was done twice, and each time a piece of iron wire was found to have been driven right through the cable, producing a short-circuit.

The presence of a 'saboteur' on board the ship was at once suggested, stirring up mutual suspicions and alarm. The 'criminal' was found out a few days later. It was the cable itself or, more accurately, its armour. The hard iron of the armour wires was too brittle and had broken to pieces under the tremendous weight of the many turns of cable coiled up in the tanks. Some of those pieces had pierced the insulation. As W. H. Russel, the *Times* correspondent accompanying the expedition, wrote: "What we had taken for assassination might have been suicide". The trouble was that, in designing the cable, emphasis was placed on its electric properties and nobody had thought of testing it for mechanical strength. But a real tragedy occurred on the morning of August 2 when the ship had completed almost three-quarters of her task. In clearing up the third trouble caused by a piece of armour wire, the cable snapped and sank. For the next nine days the *Great Eastern* made valiant attempts again and again to recover the cable, circling round the place marked with a buoy. As would be the case today, they used a tool called the grapple iron – an anchor with many flukes, often used for dragging along the bed of a river, lake or sea when searching for something. Attached to the end of an iron wire rope, the grapple tool was dragged over the ocean bottom. Three or four times they were lucky enough to catch the cable and even bring it halfway to the surface. But each time the grapnel rope would break for lack of strength. The 1865 expedition had been yet another failure, but with a difference – there was no loss of faith in the ultimate success.

A new cable was made, with an armour of more ductile galvanized iron wires, and a thirty-five kilometre supply of iron wire rope capable of standing a thirty-ton strain was secured. Improvements were made in the mechanisms and tools on board the *Great Eastern* and the ship's bottom was scraped clean of the layer of mussels and barnacles a half metre

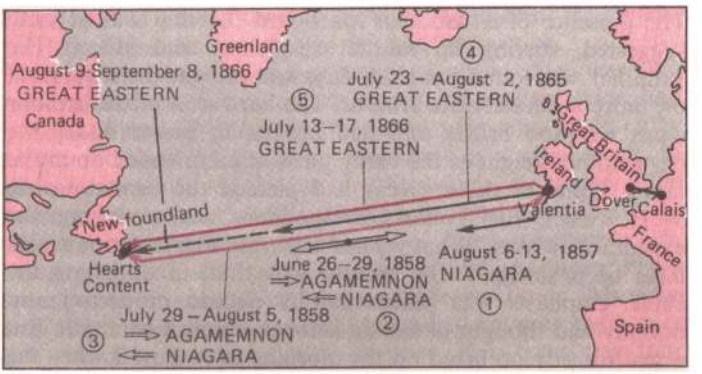


Fig. 4.11. Routes of the first five Atlantic cable-laying expeditions

thick and the long seaweed on her sides. The removal of this marine growth must have added a couple of knots to her speed.

The fifth expedition set out a year after the fourth – on July 13, 1866, the *Great Eastern* sailed again from Valentia. It was the most successful, but the least eventful of all expeditions. The cable was being laid quietly at a pace of five knots. Each time a mile's length of cable went over the sheave, a bell rang – it did so every ten minutes. Everybody was in a cheerful mood. The *Great Eastern Telegraph*, the daily newspaper produced on board the ship, carried both local gossip and European news received over the cable she was laying. Two weeks later, on July 27, 1866, the *Great Eastern* went into anchor at Heart's Content in Trinity Bay, Newfoundland. Since that day transatlantic cables have become a normal means of electric communication between Europe and America.

Inspired with the success, the *Great Eastern* accompanied by the escort ships *Medway*, *Albany* and *Terrible* put to sea on August 9 to recover the cable which had sunk the year before.

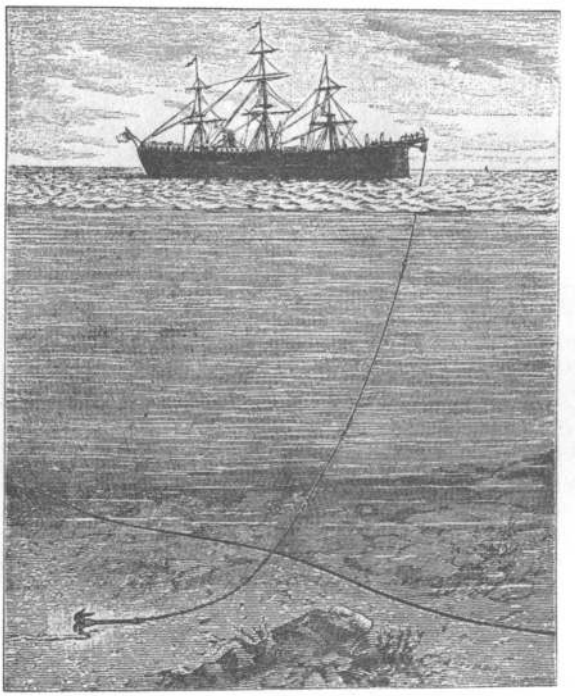


Fig. 4.12. 'Hooking' for an undersea cable (to be lifted for splicing if broken or for repair if damaged)

We will not describe that unscheduled clash with the Atlantic in detail. It lasted for three weeks, that is, longer than the laying of the new cable. At last, the cable was brought to the surface and tested. Although it had stayed in seawater for a year, it was quite good for service. A splice was made to the spare cable they had on board the ship, and the *Great Eastern* turned once more towards Newfoundland, laying the re-

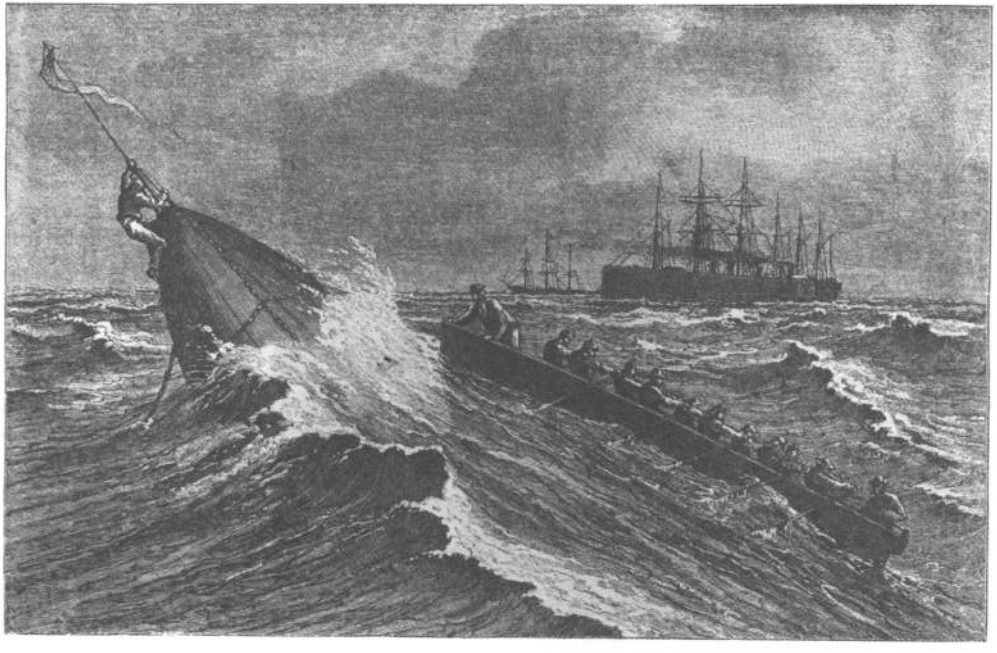


Fig. 4.13. Buoy supporting the end of the cable

maining 1200 kilometres of the line. On September 8, 1866, a second cable linked the two continents.

As Stephan Zweig wrote in the twentieth century in his essay, "The First Word from Across the Ocean" (part of his series, "Mankind's Star Hours"), "What was a miracle yesterday has become fact of life today". As he believed, the day when electric communication was established across the Atlantic marked a turning point in history. In his words, like the eternal stars, such moments shine in the nights of oblivion for ever.

Unfortunately, he sounds as prophetic in our age of nuclear bombs and space flight when he says that "The victory over time and space seemed to have united nations for ever, and their future would have been bright, were it not for their fatal blindness which drives them again and again to destroy this mighty union and to use the means that have established their power over nature in order to destroy themselves."

Scientists spoke of the event without a writer's flourish, but more to the point. The great electricians Michael Faraday and James Clark Maxwell thought high of what electric communication in general and cable lines in particular could do for the progress of science. Faraday expressed his gratitude to all those who had taken part in the Atlantic undertaking for their observation of the things that forcefully illustrated some key principles of electricity. In 1873, Maxwell was even more definite when he said that the important applications of electromagnetism to telegraphy had greatly affected pure science. As he believed, the need for knowledge in the field of electricity had spurred the activity of academic electricians, on the one hand, and had promoted the spread of knowledge among practical engineers, on the other, to a point where a major advance of science and engineering could well be expected.

The world wasn't unanimous in its view of the event. As the

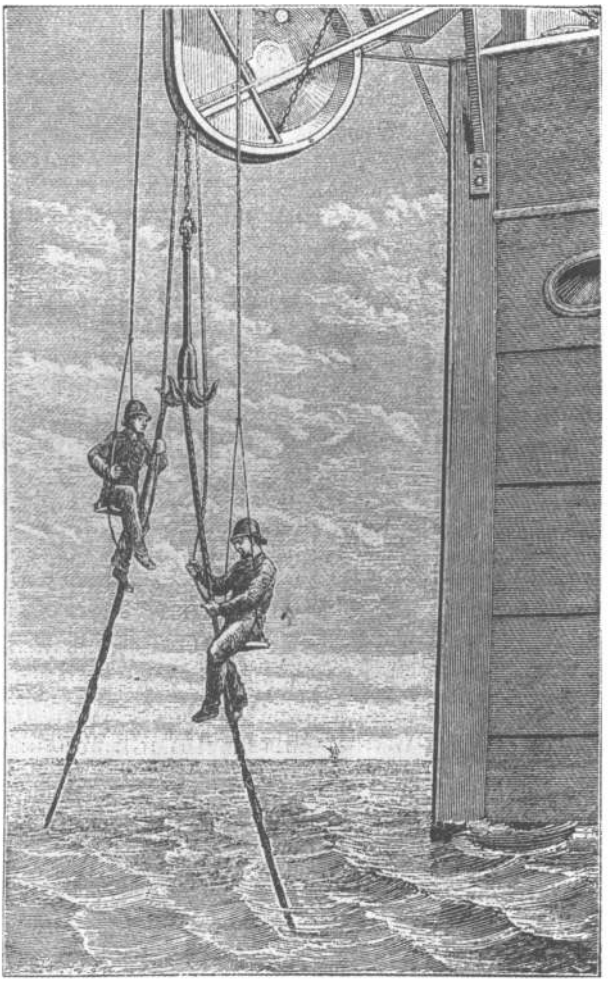


Fig. 4.14. Anchoring the cable lifted from the ocean bottom to a buoy

Shanghai newspaper *Celestial Empire* wrote: "Recall the recent past when the inhabitants of this city would impatiently wait for a cannon shot to mark the arrival of a mail boat carrying bagfuls of newspapers and magazines which would give them enough material to satisfy their inquisitiveness and thirst for news. All the fascination of waiting and the value of newspaper reports have now vanished with the advent of the telegraph. Let us admit openly that life would have been immeasurably more pleasant without it."

As would seem, Edgar Allan Poe (1809-1849), an American poet, author and critic and the originator of the detective story, should have known better than to go writing science fiction. In 1848, just a year before his premature death of inflammation of the brain, he ventured a guess about what the world would look like a thousand years ahead in his "Mellonta Tauta":

"April 2, 2848 – Spoke to-day to the magnetic cutter in charge of the middle section of floating telegraph wires. I learn that ... it was considered quite impossible to convey the wires oversea, but now ... What would we do without the Atlantic telegraph?"

He thought the Atlantic cable would be laid not a hundred or two hundred, but a thousand years later. He was 982 years in error: the 'wire' was laid through the Atlantic eighteen years after he had written his piece.

The success scored in 1866 highly stimulated the art of underwater cable making. Following the first two, a third Atlantic cable was laid from Brest in the extreme north-west of France to Newfoundland in 1869. Then three more cables crossed the Atlantic in the next five years. The last one (laid in 1874) was remarkable in that it ran from Ireland to Nova Scotia, a province of Canada, direct, with no repeater on Newfoundland, although it was 5700 kilometres long. More

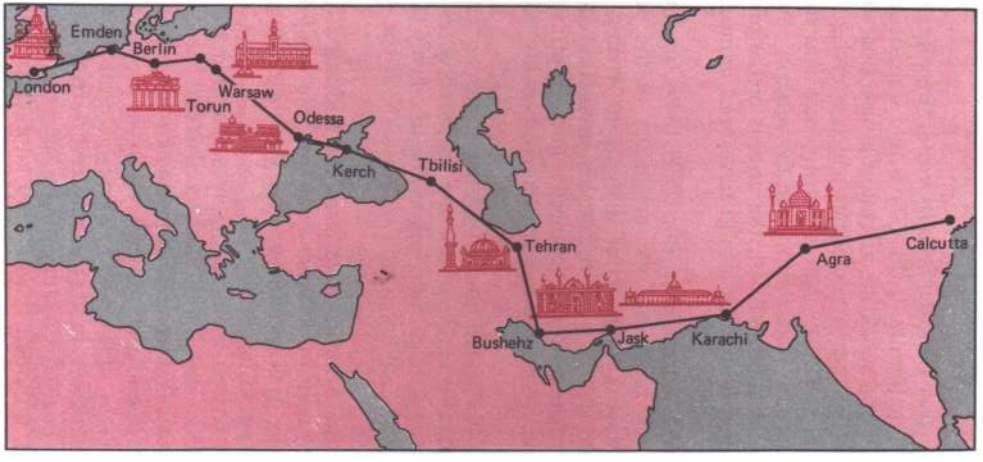


Fig. 4.15. The Indo-European telegraph line

cables were laid in the Pacific, the Indian Ocean, the Mediterranean, and the South Atlantic.

Brought to life by the advent of the electric telegraph, underwater cable in turn gave impetus to its further progress. The opportunity to cross any water obstacles stimulated the construction of overhead lines within individual countries and mixed, that is partly overhead and partly underwater, lines between countries and even continents separated by huge distances. One such line was the London-Calcutta line over 18 thousand kilometres long, built in 1867-1870.

Quite suggestively, Karl Marx noted that all of the globe seems to be enmeshed in telegraph wire. By the end of the nineteenth century, fifteen Atlantic cables had been laid, not counting the first short-lived one laid in 1858. By that time, 1750 cable telegraph lines had been installed in the seas and oceans, totalling between them 300 thousand kilometres. They handled 16.5 thousand cablegrams every day.

The cable and overhead telegraph lines totalled between them six million kilometres and they carried at least a million cablegrams and telegrams every day.

In Russia, the most impressive underwater cable lines were those between Krasnovodsk and Baku on the Caspian Sea, laid in 1879, between the Bay of De Castri and Due on Sakhalin Island, laid in 1881, and also between Odessa and Konstantinopol and between Sevastopol and Varna on the Black Sea.

In the 1880s, many improvements were made in the construction of underwater cables. Instead of seven identical wires twisted together, the cable core consisted now of a central copper wire about three millimetres in diameter and twelve copper 'surround' wires over a millimetre in diameter. The diameter of this compact core had increased by a little more than one-third but its cross-sectional area had doubled (from over eight to eighteen square millimetres). The direct-

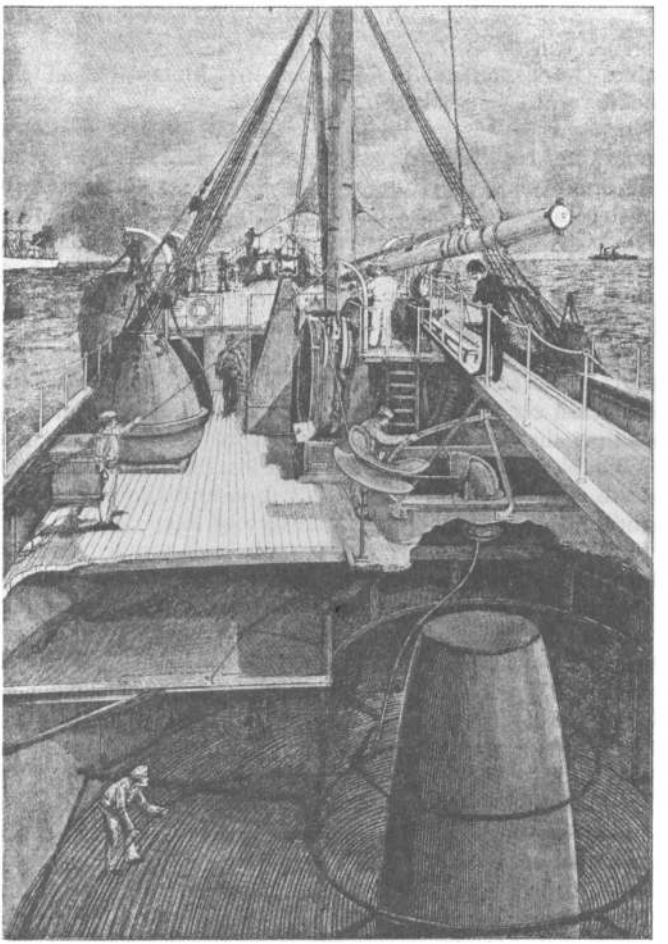


Fig. 4.16. The cable-laying ship *Faraday* built in the late nineteenth century

current resistance of the core was a mere 1 Ω/km, and so the propagation velocity of current had risen to 35 thousand kilometres per second, and so had the signalling speed. The cable armour had substantially been reinforced – instead of twelve wires, it was now made of eighteen (and even twenty-four) steel wires from 2.1 to 2.4 millimetres in diameter, with an ultimate tensile strength of 1000-1400 megapascals (one megapascal equals one million newtons per square metre). Since no outer jute wrap was applied to the armour wires, the outside diameter of the cable had been reduced to seventeen or eighteen instead of the previous twenty-eight millimetres. Although this had added to its weight in water, there was no ground for fear because the breaking strength of the cable had increased to 100-110 kilonewtons.

By 1890, a classification had been established for underwater cable grades and armouring, which has in the main survived until now. The shore ends of a cable would usually have a powerful double armour made of wires four or five and seven or eight millimetres (type AB). Where a cable was to be used under adverse conditions, such as off a rocky coast, the wires would be 7.5 and 9.5 millimetres in diameter (type C). Off-shore cables were protected with a single armour (type A) made of wire seven or eight millimetres in diameter. Transition cables laid at medium depths (100 to 1000 metres) had an armour made of wire four to five millimetres in diameter (type B) or six to seven millimetres (type E). The lightest armour would be installed on deep-water cables (types D or H).

Work on underwater and underground telegraph cable lines continued into the first third of this century. In 1902, the first cable crossed the Pacific from Canada in the north to Australia in the south. By 1930, nearly 650 thousand kilometres of underwater telegraph cables had been laid to play an important role in economics, cultural relations, politics, and military affairs. By way of underwater telegraph cable lines, the

disjointed electric communication networks on the individual continents were merged into a single world-wide system. Just forty minutes was now enough for a telegram to circle the world. Gradually, however, the purely telegraph cables were losing ground to telephone lines which could, on top of telephone conversations, carry telegraph traffic. Today, they are mainly used by railways for signalling and interlocking. The telegraph cable first emerged on railways and has now come back to railways – it has travelled a full circle.

Chapter Five

Enter the Telephone Cable

ALEXANDER GRAHAM BELL, THE INVENTOR OF THE TELEPHONE, OR TWO SENSATIONAL HOURS

The cable as we know it today owes a good deal to the telephone. Incidentally, the word 'telephone' had been coined well before man came to use this method of transmitting speech over distances by means of electric current. At first it was used in projects involving acoustics (that is, sound) and tubes. There is a concensus among the historians of electric communications that the first to come up with the idea of the electric telephone somewhere between 1849 and 1854 was Charles Bourseul, a mechanical engineer and Vice Inspector of the Telegraph in Paris. Unfortunately, he failed to carry his idea to completion.

The man who seems to have come closest to this was Philipp Reis (1834-1874), a teacher of physics at Friedrichsdorf near Frankfurt-am-Main, Germany, who spent several years (from 1853 to 1860) investigating the human ear. On October 26, 1861, he appeared before the Frankfurt Society for Physics to demonstrate what he called the telephone.

He stretched an animal membrane, to which a platinum wire, *3*, was fastened by means of sealing wax, over a small cone in the shape of a human ear, and inserted this into the bung hole of a beer barrel. The platinum wire, *4*, formed part of a battery circuit, and as anyone spoke or sang into the 'ear', the membrane vibrated in sympathy with the sound waves, and the platinum wire now touched and now moved away from the contact. In this way, the electric circuit in which the device was connected was alternately closed and opened at the frequency of the sound that acted upon the membrane. The receiver was a coil, *5*, wound with many turns of wire and

Fig. 5.1. F. Reis, a pioneer of telephony

enclosing a core in the form of a knitting needle anchored at both ends. The intermittent electric current flowing in the circuit set up a pulsating magnetic field around the coil, causing the knitting needle to vibrate and reproduce the sound augmented by a resonator, *6*, a hollow box which gave support to the solenoid.

A moderately loud tune could clearly by reproduced at a

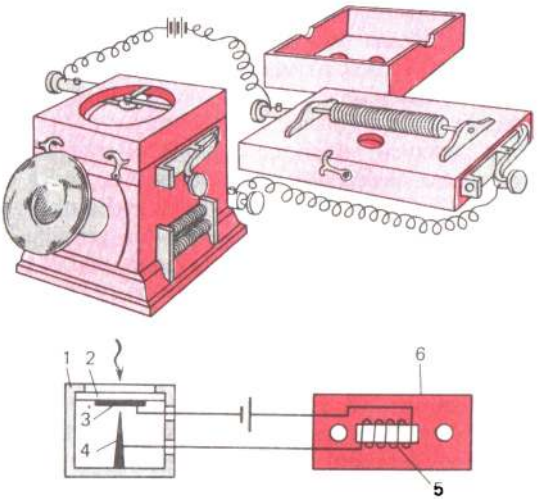


Fig. 5.2. Reis's telephone instrument: (*a*) general view and (*b*) circuit

distance of a hundred metres. The device could reproduce the sounds of a piano and wind instruments. Indistinct speech sounds could also be heard, but not more than that. Because of this, Reis's contemporaries saw in his invention a curious, but useless contraption. The trouble was that the device could only transmit intermittent current and was therefore able only to reproduce the pitch and, to some extent, strength of sound, but not the 'hues' so important in human speech. It was not until two years later that Hermann von Helmholtz (1821-1894), an eminent German scientist, who did his most original work in acoustics in its relation to optics, filled the gap in knowledge of sound sensations. Although Reis's invention was not put to practical use, his name has rightfully come into the history of the telephone. In fact, the Germans regarded him as the

inventor of the telephone during many years. In a German popular-science book on the telephone, which appeared in 1911, Reis's portrait carried a caption which read: The Inventor of the Telephone. Even today, Reis is revered in both Germanies as the trail-blazer in telephony.

The first practical telephone capable of transmitting and receiving human speech was invented by Alexander Graham Bell (1847-1922) fifteen years later. Born in Edinburgh, Scotland, he followed in the footsteps of his grandfather, the founder of a School of Elocution in London, and of his father, Professor of Elocution at London University. At the age of seventeen, he was deeply involved in acoustics and the physics of speech, and remained so until he was twenty-seven. In 1870, the Bells emigrated to Canada, and in April 1871, A. G. Bell settled in Boston, USA. He began his career as a teacher of 'visual speech' at a school for deaf mutes, but in October 1872 he set up his own school of vocal physiology for deaf mutes, stutters and similarly handicapped people, and also for those who wished to become teachers at schools for deaf mutes. In 1873 he became Professor of Vocal Physiology at Boston University's School of Elocution, where he spent many years studying electroacoustics.

Curiously, what Bell was trying to build was not the telephone but a 'harmonic telegraph'. To grasp the meaning of this name, let's go back to the electric telegraph which, in Bell's time, was rapidly spreading despite the shortage of lines. The demand for overhead lines was a way ahead of what their builders were able to supply. Stringing up several wires on the same line could fill the need only in part. Therefore, attempts were made to use each line wire in a better way by sending two or more messages over it at a time.

Back in 1837, the American physicist Charles Grafton Page (1812-1868) discovered what he called 'galvanic music'. In an electric circuit made up of a vibrating reed, an electromagnet,

and a galvanic cell, the electromagnet produced a musical note when the metal reed was set vibrating and alternately closed and opened the circuit. The note thus produced was of a fixed pitch, and it could be used for signal transmission at only one frequency. In 1869, G. Morozov (1836-1904), Professor of Physics at Kharkov University, Russia, proposed the use of several frequencies so that more than one message could be transmitted over the same wire.

As his idea went, the transmitter was to be a flexible metal plate firmly secured at one end and partly immersed in a glass vessel filled with a current-conducting liquid at the other. A current would be conveyed to the plate from a battery. Forced to vibrate at some frequency f_1, the plate would vary the resistance of the liquid between the plate and a fixed electrode also placed in the vessel. The current flowing in a single-wire d.c. circuit would change at the same frequency. The receiver could be a combination of two solenoids topped by an armature in the form of a metal strip tuned to resonate at the same frequency as the metal plate in the transmitter. It could be readily arranged that several transmitters, T_1, T_2 and T_3, be sending signals into the same wire by causing their plates to vibrate each at a frequency of its own, say, f_1, f_2 and f_3. Then each of the receivers, R_1, R_2 and R_3, would only respond to the signals of the respective transmitter. In this way, several signals differing in frequency could be conveyed over the same line without interfering with one another. The duration of signals was to be the same as in the Morse code. Morozov was unable to implement his idea, but it was followed up by others.

Communication lines, first telegraph, then telephone, came into being and developed with the advent of the electric telegraph and the telephone. In turn, advances in line operation called for improvements in the methods of transmission, or signalling – an example of feedback in engineering. The need was so urgent that the Western Union Company went so far as

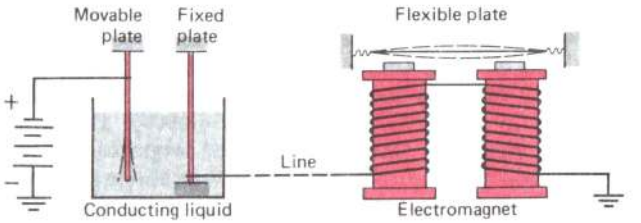


Fig. 5.3. G. Morozov's scheme for simultaneous transmission of several telegrams at different frequencies over the same circuit

to offer a huge award to any one who could tackle the problem.

Bell cudgeled his brains over the problem since 1873. But he was not alone to experiment with the 'harmonic telegraph'. Another man of importance was Elisha Gray (1835-1901), an American inventor and a manufacturer in Chicago.

Bell's plan was to use a set of vibrating steel reeds, each tuned to a different musical note, at the sending end, and a similar set of reeds tuned to the same set of notes at the receiving end. When a reed was made to vibrate, its contact point would alternately make and break the electric circuit, thus interrupting the current flowing in it. Thus several notes (as many as seven) could be sent over the same wire, that is, current at the frequencies corresponding to the pitch of the notes. At the receiving end, each reed would respond only to a signal of its particular frequency and would ignore all the others.

As far as our knowledge goes, no operational 'harmonic telegraph' has ever been built. But on June 2, 1875 during one of his experiments in which he was assisted by Thomas A. Watson, one of the reeds at the sending end had stuck to its electromagnet by chance (another chance to our score of fortunate discoveries). When Watson tried to get it going again

by plucking it (unsuccessfully because the contact point on the reed had welded to its counterpart on the electromagnet), Bell could hear at the receiving end a faint but clear sound not unlike the one given off by a string stretched taut. At that instant the telephone was born.

The welded reed worked much as the thin diaphragm did in Reis's device. In the previous experiments, the reeds simply made and broke the electric circuit. Now the caught reed vibrated slightly and induced electromagnetic waves in the transmitting electromagnet located below it. As a result, a pulsating but continuous current was sent along the circuit to the receiving electromagnet and caused its reed to vibrate in the same manner. In this lay the fundamental difference between all existing telegraph sets and the telephone. The telegraph sent current pulses which, although different in duration, had all the same amplitude. The telephone needed a continuous current whose strength and frequency would vary in precisely the same way as the original sound waves do in the air.

At first, Bell was only able to send individual sounds and not coherent speech over the wires that connected his transmitter and receiver. Another nine months and one week were to pass before the telephone became articulate.

February 14, 1876, the day when the United States celebrated the centenary of its independence, had a valuable present not so much for those in the electric communication business as for newspapers and the legal profession. It still remains a sensation, an invaluable and unfading boon for popular-science writers. On that day A. G. Bell filed an application to the Washington Patent Bureau for a patent on his invention, 'a telegraph with which human speech could be transmitted'. Two hours later, Elisha Gray filed a caveat, a formal notice of his claim to the idea of his invention, 'a device for the transmission and reception of vocal sounds by a

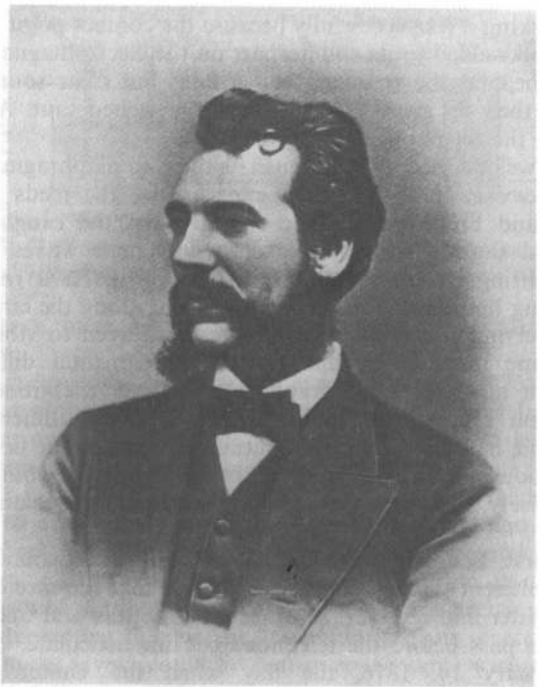


Fig. 5.4. A. Bell, inventor of the telephone

telegraph method'. He hoped with his caveat to prevent others from patenting the same idea within the period of a year.

Many articles and books, both popular and special, still tend to look at this event as a happy chance that brought world-wide fame to Bell and left Gray in the shadow. Most of them are sure that 'everything was decided by those two hours'. (Some say it was one hour, others believe it was three hours.)

Although those fateful two hours were decisive legally, there was more than that in this seemingly chance occurrence. Indeed, they reflected how things stood actually. All Bell had done in his life guided him to the invention of the telephone. Unlike his forerunners, he had spent a lot of time studying the physics of human speech and the structure of the human ear, had worked for a year in the E. N. T. (ear, nose and throat) Department of the Massachusetts Hospital and had been present at many operations.

On the day after their unexpected discovery, Bell and Watson put together the first electric telephone and experimented with it during all of the summer. In September, Bell sat down to write a patent application. He sweated over it for five months, adding this, deleting that, refining his statements, and re-making his drawings as more improvements were added to the instrument. What he basically claimed was a method and a device for telegraph transmission of vocal and other sounds by means of electric waves similar in shape to the air waves that accompany those sounds. That was the pivotal thing that Reis's apparatus lacked. Bell was granted US Patent No. 174465 on the telephone on March 7, 1876. Three days later, on March 10, he used the twelve-metre wire connecting his flat to his laboratory in the attic of the same house to transmit the first, now historic articulate phrase to Watson: "Mr. Watson, come here, I want you". And Watson answered: "Mr. Bell, I hear every word you say clearly".

A shattering legal blow at the idea that Bell was, and Gray wasn't, phantastically lucky has been delivered by Mitchell Willson, a former physicist, an assistant to Enrico Fermi, and the author of several novels in which the leading characters are mainly scientists. In his "American Science and Invention, a Pictorial History" he convincingly proves that there is no ground for thinking that Bell and Gray invented the telephone at the same time. He admits that Gray filed his caveat a mere

hour, two or three later. But while Bell's application described a nearly finished thing, Gray only put in a note of his intention to invent the telephone and of the principles, quite sound and convincing, on which the device was to operate.

The point is that Gray, as an American citizen, had the legal right to enter a caveat, while Bell who was a British subject at the time (he became an American citizen later, in 1885) had no such right. As if to make things worse, Bell who always needed money for his experiments had conceded to J. Brown of Canada the right to use the telephone in Britain for six months at a fee of twenty-five dollars a month. As the contract had it, Bell was to abstain from filing a patent application in the United States until Brown had been granted a British patent. This, too, had delayed Bell's application. That was how matters stood in the 'two hours' case.

To this we may add, as Mitchell Willson points out, that Gray himself never insisted that he had invented the telephone before Bell.

The Bell telephone used identical devices, called the Bell tubes, both to transmit and to receive sounds. Each consisted of an electromagnet, *1*, a horn, *2*, a leather diaphragm, *3*, and a lever, *4*. The lever was made fast to the diaphragm at one end, and to the armature, *5*, of the electromagnet, at the other. At first Bell used no batteries, but quite naturally the weak current induced in the transmitter could travel a distance of not more than several hundred metres.

When somebody spoke into the horn, the sound waves drove the diaphragm into vibrations. As it did so, the diaphragm actuated the lever, and this in turn moved the armature of the solenoid energized with the current supplied by a battery. Moving in step with the sound waves, the armature brought about proportionate variations in the magnetic flux that threaded the electromagnet. As a result, the

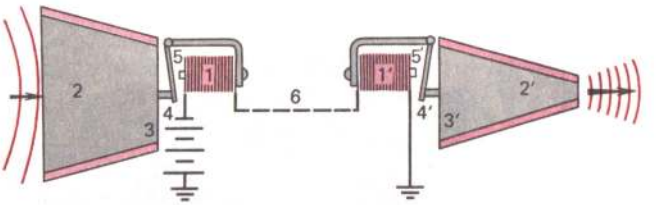


Fig. 5.5. Bell's telephone as sketched in his patent of March 7, 1876

direct current flowing in the single-wire circuit, *6*, connecting the transmitter and receiver was changed into an alternating current at the frequency of the sound spoken into the horn. This alternating current set up an alternating magnetic field around the electromagnet, *1'*, in the receiver, its armature, *5'*, attracted the lever, and this caused the diaphragm, *3'*, in the receiver to vibrate in exactly the same manner as its counterpart did in the transmitter. Finally, the horn, *2'*, of the receiver reproduced the same sounds as went into the horn, *2*, at the transmitting end.

On June 25, 1876 Bell, the twenty-nine years old, demonstrated his telephone for the first time at the Philadelphia Centennial Exhibition of 1876. Sitting on its jury was the famous Lord Kelvin. Highly delighted, he said it was the best invention he had seen in the United States and the greatest of all the miracles related to the electric telegraph.

Now let us turn to Gray's idea. The membrane in his transmitter was attached to a small iron rod immersed at the opposite end in a vessel holding a fluid of low electrical conductivity, which was part of a battery circuit.

As sound reached the membrane, it vibrated the rod immersed in the fluid. The rod's vibrations changed the resistance of the circuit's part containing the fluid (not unlike Morozov's idea), so that a fluctuating current passed around

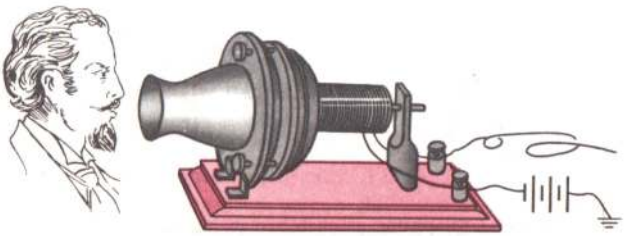


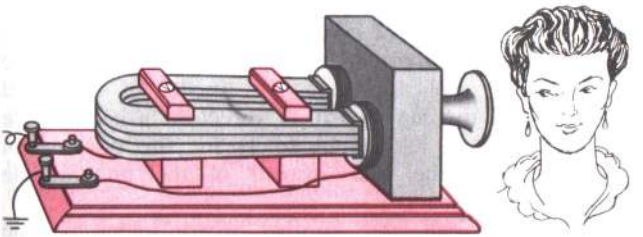
Fig. 5.6. The transmitter and receiver in Bell's telephone of 1877

the circuit. At the receiving end, as in Bell's case, the wires of the circuit passed into the coil of an electromagnet inside which another small rod of soft iron was attached to a membrane. Thus the sound reaching the sending diaphragm was electrically duplicated by the receiving diaphragm.

Gray's fluid transmitter was less convenient and reliable in operation than Bell's electromagnet-operated device. Therefore there is every reason to say that Bell was well ahead of Gray not only in time but also in performance.

A year later, Bell improved his instrument. He replaced the leather diaphragms with metal ones – they were lighter in weight and possessed magnetic properties. Also, he used a permanent magnet in the receiver. This markedly extended the bandwidth of the instrument and improved the quality of speech transmission.

The world's first telephone line three kilometres long (it was an overhead type) linked the Mayor of Boston's office to his residence in the suburb in the autumn of 1877. In Europe, the first telephone line two kilometres long (likewise, an overhead one) was put in operation between the Central Post Office and the Central Telegraph in Berlin on November 5, 1877. By the end of the same year, the United States had 9300 telephone instruments in operation. On January 25, 1878, the Bell



Telephone Company opened the world's first commercial telephone exchange at New Haven, Connecticut, midway between Boston and New York. At first, it served twenty-one subscribers, but in about a month their number rose to fifty.

Once invented, the telephone spread all over the world with amazing speed. The history of engineering has known very few devices that have become an integral part of man's daily life so rapidly, on such a wide scale to stay for so long.

In Europe, the first fifty telephones were installed in 1877, and in 1878 their number increased to a thousand. The first telephone exchange in Paris was put in service in 1879, and in Berlin in 1881.

In Russia, the first small private telephone exchanges were installed at factories in the Ufa Province in 1880. In the same year, Russia's Defence Ministry inaugurated its first overhead telephone line about a kilometre long, although the earliest tests of the telephone in Russia were made as early as 1878, using the overhead and cable telegraph lines laid across the Transund Strait in the Baltic Sea.

On July 20, 1881, an overhead telephone line one and a half kilometres long went into operation in Nizhny Novgorod (today, the city of Gorky). It linked the George Pier on the river Volga to the residences of the managing directors of the

Druzhina Steamship Company. Its wooden poles carried two single-wire circuits made of iron 'telegraph' wire. The return path in each circuit was provided, as in telegraph lines, by the ground. In their application to the Minister of Post and Telegraph, the Druzhina board of directors asked for "a permission to install telephones solely for the purpose of sending orders to the Pier instead of the unavoidable messengers".

A month and a half later, another private telephone line went into operation at Fellin (now Vilyandi in Estonia). It was eight hundred metres long and had fifteen poles about seven and a half metres tall, which carried steel wire three millimetres in diameter.

In 1882, the first telephone exchanges were built in the Russian major cities of Moscow, St. Petersburg, Odessa, and Riga. At first, the Moscow Central Telephone Exchange, officially opened on July 13, served twenty-six subscribers. The single-wire subscriber lines terminating at the switchboards were led through openings in the ceiling to a metal post on the building's roof. The post carried a great number of porcelain insulators. Spreading out from the post in eight radial directions were the wires of overhead lines strung on posts and poles. At first, the wires were of steel 2.2 millimetres in diameter. Later, in the latter half of the 1880s, they gave way to bronze wires 1.4 and 1.25 millimetres in diameter.

Bell was well aware of the significance and prospects of his brainchild. In March 1878, he predicted: "It may be imagined that the cables of telephone lines will be laid in the ground or strung in the air, and their arms will link residences, rural houses, shops, and factories to the main cable going to a central exchange where all of those wires will be connected in various combinations, thus establishing contact between any two points in the city". As he went on to say, "In the future telephone lines will link central exchanges in various cities, and

a person in one part of the country will be able to communicate by word of mouth with any other person a long distance away from him".

Already at the telephone's birth, its inventor clearly saw what networks of city and intercity telephone lines could do.

As most telegraph lines of that time, the early telephone lines were aerial or overhead, although attempts were made to use underground telephone cables so as to replace the bare overhead wires in densely populated cities with their rapidly ramifying telephone networks. There was also the need to cross navigable rivers and to use bundled wires over bridges and in railway tunnels. A few years after the telephone service had become a regular feature, the streets and the rooftops in major cities presented an ugly sight because of the cobwebs of telegraph and telephone wires. The pole lines running each side of almost every street would carry as many as one hundred-fifty to two hundred or even four hundred-fifty to five hundred wires. They were highly vulnerable to the wind, rain, snow, and other elements which caused frequent and sometimes serious damage. Another source of trouble came with the advent of strong-current lines first for street lighting (the electric bulb was invented at about the same time as the telephone) and then for tramcars because they induced heavy noise in telephone lines. Sometimes this noise was so heavy that it disrupted telephone communication altogether, the more so that the telephone circuits were of the single-wire types.

For the first time seven-conductor cables ten to twelve hundred metres long, also connected in single-wire circuits, were laid on the Brooklyn Bridge in New York in 1880. At the end of 1882, two conductors (of an unknown number of wires), three hundred-sixty and four hundred-fifty metres long, were laid from the telephone exchange in Boston to the subscribers in three-inch iron pipes embedded in concrete. In Russia the

Fig. 5.7. Overhead city telephone lines in the early 1880s

L. SAUTER & CO. RINGS
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JEWELLERS RINGS
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first telephone cable was laid across the river Oka in 1885 as part of the Nizhny Novgorod City telephone network. The cable one kilometre long was made up of ten copper conductors each insulated with gutta-percha and covered with cotton yarn. To avoid inductive pick-up (a source of noise), each insulated conductor was wrapped with tin foil – it acted as a shield. All the shields were connected to earth (that is, grounded) by a common wire. The cable was armoured with round iron wires four millimetres in diameter, and its sheath was hemp yarn treated with an asphalt compound.

In 1891, the first submarine telephone cable linked Britain and France. By that time, over a half-million telephone instruments were in use throughout the world.

A FEW PIECES OF THEORY

What was, and still is, the purpose of communication cables? To transmit intelligence, that is, all sorts of data, over distances. Intelligence may be in the form of various messages, such as telegrams, arrays of numerals and letters emerging from computers, human speech, songs, music, and pictures which may be still (as in facsimile service) or moving (as in TV). Together with other supporting apparatus, cables are arranged into what are known as communication lines or links which may span distance running into thousands of kilometres.

As any manufactured product, a cable is turned out to have a well-defined size and mass. Telephone cables come from manufacturers wound on wooden reels, or cable drums which are a fairly common sight in city streets. Each drum carries a well defined 'delivery' length of cable which varies from one type of cable to another. This 'delivery' length of typical long-distance (or toll) cable is 825 metres. A line 500 kilometres long would require 605 delivery lengths of cable joined end to end.

Cable design has a vital bearing on the performance of the line using it. In turn, the services to be supplied by a line govern the cable design and manner of manufacture.

Since we are concerned with the telephone, the fastest, most convenient and most popular means of communication in the twentieth century, let us see what the telephone cable is like. Once we have formed a general idea, it will be an easy matter to learn any particular, specific design.

The telephone cable serves to transmit human speech which is a combination of various complex sounds. The human lungs force a stream of air through a slot, called the glottis, formed in the upper part of the windpipe by the vocal chords – a pair of string-like muscles. As we speak, the vocal chords are set vibrating, and the vibrations are passed onto the stream of air passing through the glottis. That's how a pressure wave, or a sound, is produced.

Sounds differ in strength, pitch (tone, that is, the degree of highness or lowness), and timbre (quality of sound). A young man would usually produce strong sounds, and an old man weak sounds. (Children's sounds may make you wonder at how strong they are!). The sound of a jet plane is immeasurably stronger than that of a mosquito. On the other hand, a mosquito produces a high-pitched whine, and the whistle of a steamship a low-pitched rumble. The pitch of a sound depends on its frequency, that is, the number of vibrations per second.

The unit of frequency is one cycle of vibrations or, simply, one cycle, per second. This unit is named the hertz (Hz) after Heinrich Rudolf Hertz (1857-1894), the German scientist who experimentally verified the existence of electromagnetic waves in 1886-88. The heavy strings in the left part of a piano, when struck with their hammers, vibrate slowly, and the sounds they produce are at a low pitch; they are called bass sounds. The lowest note produced by a piano has frequency twenty-seven hertz, which means that the string vibrates twenty-seven times

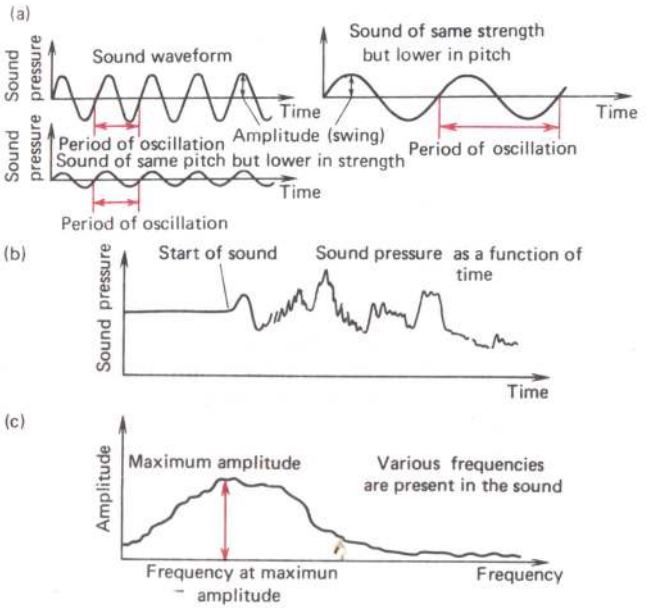


Fig. 5.8. Sound waveforms: (*a*) simple sounds; (*b*) and (*c*) complex non-periodic sounds

every second. The strings in the right-hand part of a piano are short and vibrate at a high frequency, and so they produce high-pitched or treble sounds. A piano's sound of the highest pitch has frequency 4000 hertz. The note produced by the piccolo, a small flute, is an octave higher than (that is, twice as high as) that of the ordinary flute and may be as high as 9000 hertz in frequency.

Sounds of the same strength and at the same frequency may

differ in quality. A tuning fork produces a simple note, that is, a sound at one frequency. Musical instruments produce complex notes, that is, a combination of several frequencies. They are periodic sounds. The most complex sounds of all are noise and human speech; they are non-periodic sounds. When speech sounds are sung, rather than spoken, they become complex periodic sounds. As has been noted, Reis's telephone could transmit songs and music, but not plain human speech.

Any sound of human speech consists of a main note, or the fundamental tone, and several higher-pitched notes, or overtones. It is overtones that impart individuality to voices and enable us to recognize the talker although he or she may be invisible to us.

Voices are classed according to the frequency limits within which the fundamental tone lies. For the bass these limits are between 80 and 300 hertz, for the baritone between 100 and 400 hertz, for the tenor between 125 and 500 hertz, for the contralto (the lowest female voice) between 150 and 600 hertz, and for the soprano (the highest female voice) between 250 and 1100 hertz. Within the above limits, the sound waves have the largest amplitudes, or swings. The overtones are many times higher in frequency than the main tone, but their amplitudes are only fractions of that of the fundamental. In the final analysis, any complex sound of human speech may be said to consist of a multitude of simple components varying in amplitude and ranging in frequency from 80 to 6000 hertz.

Speech sounds average ten microwatts in power (one microwatt is one-millionth of a watt). The power carried in a loud cry may be as large as a thousand microwatts, while in a faint whisper it may be as small as one hundredth of a microwatt. How small these figures look can be seen if we compare them with the megawatts and gigawatts, that is, millions and thousand millions of watts produced by present-day power plants. It is immediately seen that power cables

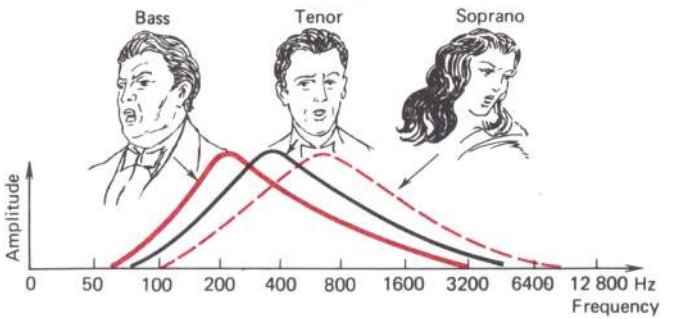


Fig. 5.9. The frequency spectra of human speech and singing

must of necessity drastically differ in design from communication cables.

Picked up by the outer ear, or auricle, sound waves set the eardrum, or tympanum, in vibrations. Located between the outer ear and the middle ear, the vibrating eardrum causes the hammer to strike the anvil and the stirrup to transmit the vibrations to the fluid filling the semicircular canals in the inner ear. The vibrations of the fluid are recognized by the auditory nerve as sounds. The human ear can discern sounds ranging from 16 to 20 000 hertz in frequency. It is most of all sensitive to sounds at frequencies between one and two thousand hertz.

Now let us take a look at Figure 5.10 explaining how the telephone works. During a conversation, the sounds produced by one subscriber, *A*, are picked up and converted to electric oscillations by the telephone transmitter, or microphone. The microphone is basically a case enclosing two brass electrodes, one fixed and the other movable in the form of a thin circular diaphragm, to which direct current is conveyed from a battery. The space between the two electrodes is loosely filled with 0.5 to 1.25 grams of carbon granules. Driven by sound waves, the

diaphragm brings a varying pressure to bear upon the granules. This causes variations in the resistance that the granules present to the current and, as a result, a change in the resistance of the entire microphone circuit. The current flowing in the circuit varies in proportion, exactly following variations in the sound waves.

The microphone boosts the electric oscillations about a hundred times. The average power of sound waves during a quiet conversation is about ten millionths of a watt. The output power of a typical telephone transmitter is one milliwatt (one milliwatt is one thousandth of a watt).

The pulsating current is then converted to an alternating current by a transformer, *Tr*. This current flows in the connecting line and finally reaches the other subscriber, *B*, where it is picked up by a telephone receiver, or earphone. The earphone consists basically of a permanent magnet and pole-pieces which carry coils, and a soft-iron diaphragm. The pole-pieces and the coils make up an electromagnet. During silence, the diaphragm is always attracted to the permanent magnet so that is flexed all the way to the left (as seen in Figure 5.10). When an alternating current traverses the coils of the electromagnet, it sets up an alternating magnetic flux. This flux is alternately added to or subtracted from the permanent flux. When the alternating flux is subtracted from that of the permanent magnet, the diaphragm is free to flex all the way to the right; when the two fluxes combine, it is pulled back to the left. In this way, the diaphragm is caused to vibrate. The vibrations of the diaphragm (with a swing of as little as 0.000002 to 0.01 millimetre) produce sound waves which are similar in frequency and shape to the alternating current energizing the electromagnet. Thus, the earphone produces the same sounds as act upon the diaphragm in the telephone transmitter. The earphone is typically sensitive enough to respond to signals as small in power as one-millionth of a watt.

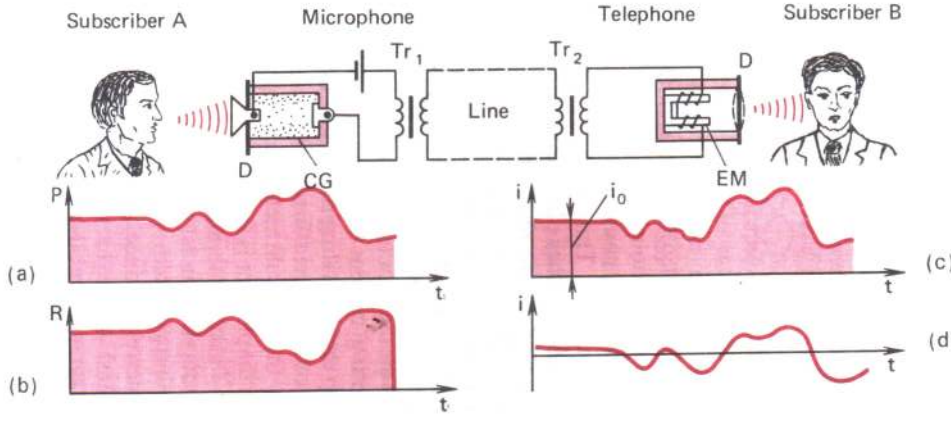


Fig. 5.10. Principle of telephone transmission: (*a*) change in sound pressure; (*b*) change in the resistance of the carbon granules in the transmitter; (*c*) change in the current flowing in the transmitter circuit; (*d*) change in the current flowing in the line; *D*, diaphragm; *CG*, carbon granules; *Tr*, transformer; *EM*, electromagnet and pole-pieces

Since any conversation is a two-way activity, each subscriber has both a transmitter and a receiver. At first, they were made separate, but nowadays they are built together into what is called a handset. As a rule, the microphone circuits of all subscribers are energized from a central battery or a similar source at a telephone exchange.

Of course, what any subscriber wants to hear is an intelligible speech. To fulfil this requirement, it is enough to transmit speech sounds ranging from 300 to 3400 hertz in frequency. A wider bandwidth of 50 to 12 000 hertz is needed for the transmission of music and singing.

The words 'low frequency' and 'high frequency' are used very often, but these are relative terms. For power engineers who have to do with what is known as industrial or power frequency (50 hertz in Europe and 60 hertz in the United States), frequency 3000 hertz would seem very high, but to radio engineers using very high, ultra high, super high and extremely high frequencies (running up to a million million hertz), this figure would certainly appear very low indeed. In wire communications, the frequencies below twelve thousand hertz are known as voice (or audio) frequencies, and those above that figure as high (or carrier) frequencies.

A LYRICAL ASIDE

When they deal with science and technology of today, books sound dry and 'down to earth'. Not so when they come to the history of science and engineering – then they are more romantic, seem to be filled with more passion and informal beauty. This is not a matter of fashion, but that of a longing for something we have known in the past. On top of the poetry of bygone days with its clear and ringing rhymes, vintage tangos and Gypsy songs, we are now looking for something romantic in the thoughts and doings of the past centuries. That's why

even minute details in the laying of the Atlantic telegraph cable seem to us interesting, significant and romantic. To the people who worked on the project, it was close to a drudgery. It may so happen that today's R & D, specs and other technocratic chores and paraphernalia would seem romantic to the generations to come. It may so happen that they will see a great lure in what we take today as the hardships of everyday life, the pains of creation and sometimes futile effort of scientific search. Yes, they will be able to see all this if we preserve evidence of our efforts and accomplishments. As Vladimir Lidin, a Soviet author, puts it poetically, succinctly and, as always, with a bit of plaintive sadness in the words of one of his characters, "Like trees, history sheds its leaves, and, although fallen, each carries a bit of the past and we, living today, should yield not a single little leaf to the winds of time, it is our moral duty to preserve them".

Of late, scientists have increasingly more been speaking of the beauty of science. Of the harmony of parts that make up a whole thing. Of the elegance of logic. Of the impressive symmetry of equations. "An ugly looking equation cannot be correct", they say. The great equations of electrodynamics derived by J. C. Maxwell have become the standard of symmetry and beauty. As Paul Dirak, a prominent British physicist of the twentieth century, wrote during his visit to Moscow University, "A physical law must be mathematically elegant".

The simplicity and rationality of design equations, the ingenuity and artistry of an experiment, the audacity and terseness of an engineering treatment do all produce a sensation of beauty. Therefore...

ANOTHER PIECE OF THEORY

Thus electric signals differing in frequency are transmitted, during a telephone conversation, over a two-wire circuit, that is, a circuit which consists of two insulated conductors. All along the circuit, the conductors remain the same in diameter, and their insulation remains likewise the same in design and thickness. Therefore, the circuit's constants remain unchanged over its entire length. As is customary to say in electrical engineering, what we have is a distributed-constant circuit.

Each elementary section of a two-wire circuit is described by four constants. Two of them are its resistance, R, and its capacitance, C, we learned about in Chapter 4. True, what we had there was the capacitance of a single-wire line, and now we will deal with that of a two-wire circuit. However, the physical meaning remains unchanged, for two conductors separated by a dielectric likewise act as a capacitor, but its capacitance is described by a more intricate equation. In contrast to d.c. resistance, its a.c. equivalent depends on frequency as well as on the already familiar quantities.

A third parameter, which we didn't consider when we were dealing with d.c. telegraphy, is the inductance, L. In flowing through a circuit, an alternating current sets up an alternating magnetic field around it. In turn, this alternating field induces an electromotive force, EMF, in the same conductors that carry the alternating current producing it. Actually, this is a counter-EMF because it acts to bring down both the voltage across and the current in the circuit. This action is known as self-induction, and its quantitative measure is the inductance. It depends on the size of the conductors, the spacing between them, and the permeability, μ, of the conducting material. The unit of inductance is the henry, so named after Joseph Henry mentioned earlier in this book.

The fourth constant is the conductance through the insula-

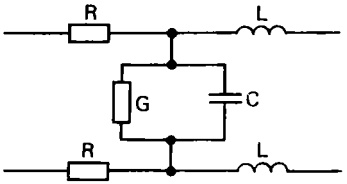


Fig. 5.11. Primary constants of a cable transmission line

tion, often called leakance, G. Although, in contrast to metals, dielectrics have a very large resistivity, it is not infinite. Therefore, when a potential difference exists between the conductors of a circuit, what is known as the leakage current flows through the insulation. The quality of the insulation used in a d.c. circuit is evaluated in terms of insulation resistance, R_{ins}. Since it is high, the d.c. leakance, G_0, which is the inverse of R_{ins}, is extremely low and the leakage current is negligible. The picture is not so simple with an a.c. circuit. Now one more current flows through the insulation, known as the absorption current, which arises when polar molecules (those carrying unlike charges) align themselves with the electric field. Since the electric field is an alternating one, the molecules change their orientation all the time, and this entails losses. They may be thought of as arising from an increase in the leakance, that is, due to an impairment in the insulation. These losses vary with the frequency f of the current transmitted through the circuit, the insulation capacitance C, and what is known as the loss angle, δ, of the insulation.

The leakance at a.c., proportional to the loss angle (rather, to the loss tangent), is

$$C_f = \omega C \tan \delta = 2\pi f C \tan \delta$$

where $\omega = 2\pi f$ is the angular frequency and $\tan \delta$ is the tangent of the loss angle or, simply, the loss tangent.

Every elementary section of a two-wire circuit contains the resistance and inductance of each conductor, the capacitance between the conductors, and the conductance through the insulation (or the loss conductance). In transmission line theory, they are collectively called the primary constants of a line.

Converted from sound waves and boosted by the telephone transmitter, the electric signals at audio (or voice) frequencies gradually lose their strength, that is are attenuated, as they travel down the line from the calling to the called party. In the process, some power is spent to overcome the resistance of the conductors, some goes away, or is dissipated, as heat (of course, the heat build-up in a telephone cable carrying a current of just a few milliamperes is nothing compared with what happens in a power cable, but some power is lost all the same). Partly, the transmitted power is brought down by the action of the back-emf of self-induction. Lastly, some of the transmitted power is lost with the leakage current through the insulation due to both its capacitance (as will be recalled, an alternating current flows through a capacitor in much the same way as a direct current moves through a conductor) and its conductance.

All in all, the power P_l arriving at the receiving end of a line l long is a good deal smaller than the input power P_0. The total loss in the power of the signals transmitted over a line is described as the natural attenuation of that line. It is given the symbol a and measured in decibels, dB, which is a logarithmic unit for comparing power, current, voltage and field strength ratios:

$$a = 10 \log_{10} P_0/P_l$$

It is one-tenth of the bel

$$a = \log_{10} P_0/P_l$$

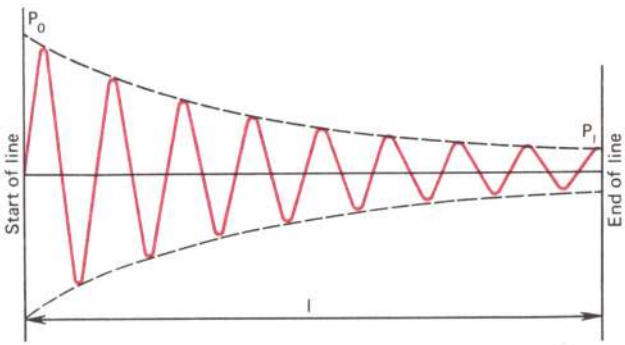


Fig. 5.12. Attenuation of the signal transmitted over a line

which, as the reader has surely guessed, has been named after A. G. Bell, the inventor of the telephone.

There is another logarithmic unit used to express the attenuation of currents or voltages along a transmission line. It is called the neper so named after John Napier (1550-1617), an Englishman famed over the world as the inventor of what we now call the natural or Naperian logarithms. Thus, expressed in nepers, the attenuation of a line is

$$a = \frac{1}{2}\log_e(P_0/P_l)$$

where e is the base (2.71828) of Naperian logarithms.

Nepers can be converted to decibels by multiplying by 8.686 or, in round numbers, by 8.7. That is, one neper is equal to 8.7 decibels. Conversely, decibels can be converted by dividing by 8.686. That is, one decibel is approximately equal to 1.15 nepers.

The bel and, especially, the decibel are widely used to describe how much a signal is amplified, that is, the gain of the signal. There is a psychophysiological law which states that the

sensation of loudness varies in proportion to the logarithm of power ratios rather than in proportion to power ratios.

Nowadays, decibels have come to be a part of our life, especially for urban residents, because of a progressive increase in the loudness of street and other noise.

Dry leaves blown by the wind produce a noise ten decibels strong, normal speech and quiet music are evaluated at forty decibels, the clatter of crockery and the conversation of the guests at a restaurant produce fifty decibels, and the engine of a truck, seventy decibels. The horn of a car yields ninety decibels, and a jet airliner drives at us as much as one hundred and twenty decibels if we are close to it. Most rock groups fall, perhaps, very short of it. At one hundred and thirty decibels, we come to what is known as the threshold of pain.

As has been noted, the output power of a telephone transmitter is one milliwatt (10^{-3} W), and the least that a telephone receiver is able to respond to is one microwatt (10^{-6} W). It follows, therefore, that the attenuation of a line, however long, ought not to exceed

$$a = 10 \log_{10}(10^{-3}/10^{-6}) = 10 \log_{10} 1000 = 30 \text{ dB}$$

(In case you don't know, the logarithm of 1000 to base 10 is 3). In practice, a somewhat lower attenuation of around twenty-eight decibels is permitted. Even then, the telephone receiver picks up as little as 1/630th of the power sent into the line by the telephone transmitter. The efficiency of a line is thus less than two tenths of a per cent. While designers working on power transmission lines, both overhead and cable, make every effort to bring down the power losses to as low a figure as practicable, that is, to a few per cent, in communication lines 99.8% of the power is lost. But there is nothing frightful in that, for the primary objective for a communication line is to transmit intelligence and not power. What communications engineers strive for is the quality of telephone conversations.

The limit of attenuation set at thirty decibels applies to any line between two users, be it in the same community or at points spaced a whole continent apart. At an attenuation of thirty-five decibels a mere one three-thousandth of the input power reaches the telephone receiver, and it cannot produce anything but an extremely faint sound.

So that the performance of cables could conveniently be compared, their primary constants are referred to a unit of length, which may be a mile or a kilometre. The natural attenuation of a line per kilometre run is usually called the attenuation constant. It is symbolized by the Greek letter α (alpha), and is expressed in decibels per kilometre run,

$$\alpha = a/l$$

As has been noted, the power losses in a line are due to the four primary constants R, L, C, and G. Quite logically, they affect the attenuation constant as well. Lest the reader should be distracted by the beautiful symmetry of a complete equation, we will use two approximate ones instead. Thus, at audio (voice) frequencies,

$$\alpha = \frac{1}{2}[\omega C(R - \omega L)]^{1/2}$$

and at high (carrier) frequencies,

$$\alpha = (R/2)(C/L)^{1/2}$$

Obviously, a lower attenuation constant means that the same conversation can be carried over a longer distance by the same cable, that is,

$$l = a/\alpha$$

Reduction in α has been among the key objectives sought by the designers of communication cables throughout their history.

The attenuation constant is one of what are known as the secondary constants of cable. In the two above equations, the R and the L apply to both conductors of the circuit, and its G has been neglected. It may be added that since the constants are taken for the two circuits, they are often quoted in their respective units per loop kilometre.

OLIVER HEAVISIDE'S CONDITION

The short biographies of Oliver Heaviside (1850-1925), an outstanding British mathematician, physicist and electrician, tend to describe him as a shy and reclusive man, an unpredictable, sickly, and stubborn, difficult person, preposterous and lonely. As they say, he used to sleep by day and to make his experiments and write his papers at night. They also say that he was able to work only after he had raised the temperature in his tightly closed room with the blinds pulled down to as high as thirty degrees Celsius. We will not argue the point. But what seems far more important is the fact that he was a hard-working man who could see far ahead of his time, proud and intolerant to imperfection, and a brilliant theoretician. A Fellow of the London Royal Society and the author of a five-volume monography, "Electromagnetic Theory", Heaviside devised his now famous operational calculus to deal with transients in electric circuits, still in use in electrical and radio engineering. He was the first to suggest the existence of an ionised layer in Earth's atmosphere in 1902. Later called the Heaviside layer, it is capable of reflecting radio waves and extends out from sixty to five hundred kilometres above the ground. It was not until 1924 that the Heaviside layer was discovered by experiment, and since then it has been the basis of short-wave radio.

In 1893, Heaviside made public his findings in which he discussed how the inductance of a cable line could affect the

Fig. 5.13. Oliver Heaviside, an eminent British mathematician, physicist, and electrician

propagation of speech currents over the line. He pointed out that the attenuation could be brought down by increasing the inductance of the line artificially, such as by placing what later came to be known as loading coils in the line at regular intervals. He showed that the attenuation would be at its lowest value on satisfying the following condition

$$R/L = G/C$$

or

$$RC = LG$$

This optimal ratio of all the four primary constants of a cable has since been known as the Heaviside condition. When it is satisfied,

$$\alpha = \alpha_{\min} = (RG)^{1/2}$$

At first, as has happened in the history of engineering more than once, his idea was ridiculed in Britain. In less than a decade, however, it was realized in a convincing manner and on a large scale. Which manner we will see in a later chapter.

Heaviside derived his relation, using the complete equation of the attenuation constant. Among the many books on cables and communication lines known to this author, only one going back about a half-century in time uses the Heaviside transform and differentiation of the complete equation. The remaining ones derive the Heaviside relation from approximate equations. We, too, will use them. Before doing that, however, let us see how ordinary cables come up to this requirement. Let us take as an example a cable in which the core is 1.2 mm in diameter and uses cotton yarn and air as insulation – such cables made their appearance in the early 1890s. The telephone circuit made up of this cable would have the following constants: $R = 32\ \Omega$/km, $C = 5 \times 10^{-8}$ F/km, $L = 0.8 \times 10^{-3}$ H/km. It is usual to take the G value at the mid-frequency of the speech band, that is, at $f = 1600$ hertz (hence, $\omega = 2\pi f \approx 10\,000$ rad/s), and at $\tan \delta = 5 \times 10^{-3}$. Therefore,

$$G = \omega C \tan \delta = 10^4 \times 5 \times 10^{-8} \times 5 \times 10^{-3} = 2.5 \times 10^{-6}\ \text{S/km}$$

It follows, therefore, that

$$\begin{aligned} RC/LG &= (32 \times 5 \times 10^{-8})/(0.8 \times 10^{-3} \times 2.5 \times 10^{-6}) \\ &= (1.6 \times 10^{-6})/(2 \times 10^{-9}) \\ &= 800/1 \end{aligned}$$

The above relation as well as the simplified equations written earlier suggest several approaches to reducing the cable attenuation. Let us discuss them in turn. To begin with, we should discard any attempt to increase G – that would mean an increase in loss conductance, or leakance, that is, a major impairment in insulation performance. Hence, one valid approach is to reduce the resistance of the conductors. This can be done in any one of two ways. One is to use a material whose resistivity is lower than that of copper. The other is to increase the diameter of the conductors. Unfortunately, copper can hardly be replaced as a material for cable conductors – the only metal that has a resistivity about ten per cent lower is silver. But it is a precious metal and it would be scarcely an economic preposition to use it. However, it has been done in at least one case where money was no object. It happened during World War II when the United States Treasury handed over fifteen thousand tons of silver to make windings for the mammoth electromagnet that was to be used to separate the isotopes of uranium. For one thing, however, the silver was as closely guarded as in the Treasury vaults. For another, 99.9 per cent of it went back to those vaults when the isotope separator was dismantled and the coils were melted down again.

An increase in conductor diameter is not attractive money-wise: a prohibitively larger amount of copper would be used up, the cables would become larger in size and in weight and, most importantly, the resistance of the conductors would be reduced only in a small proportion.

Still another approach could be to reduce the capacitance of the cable. Although it wouldn't call for a greater amount of copper, this approach would be as ineffectual as the previous one – it would take a greater quantity of insulation to make it heavier, and this would again cost more money. In the past hundred years, the capacitance has been reduced only slightly.

The third approach is the one proposed by Heaviside – that

is, to increase the inductance of the cable – it can conveniently be increased tens and even hundreds of times.

Despite the Heaviside condition, however, the drive for an ever lower capacitance has been the keynote through all the periods and phases in the development of communication cables. This drive has been bearing ingenious designs and processes, and it makes all the sense today as it did before.

AN AVALANCHE OF INVENTIONS

Telephone cable design and manufacture in the 1870s. During the first five years since the invention of the telephone, it was usual to design and make telephone cables in much the same way as underground telegraph cables. By a process proposed in 1869, copper wires were insulated with cotton yarn boiled in paraffin wax and wound onto the wire in two opposite directions. As many insulated conductors as was necessary were then drawn into a lead pipe, and the pipe was coiled on a drum. A fully wound drum was then dipped in a tank filled with molten paraffin wax. One end of the lead pipe was coupled to an air pump, and this forced a stream of paraffin wax through the pipe so as to drive out all air. Thus treated, the cable was then passed through a cold water tank and wound on another drum – exposed to the cold water, the paraffin wax filling the pipe turned solid. Finally, the cable was drawn through a reducing die. That was the first time when a filler was used to keep moisture out of a cable.

A completely different process was proposed in 1875. Cotton yarn was not boiled in paraffin wax before it was applied to wires. Insulated with two or, sometimes, three plies of insulation, each conductor was first dried in an oven (that was the first time drying was used in cable manufacture) and then treated with molten paraffin wax or hot paraffin oil. A group of insulated conductors were then wrapped with jute, hemp or

other fibrous material and again treated as each individual conductor – that is, dried and impregnated. The finished core was then drawn into an iron or cast-iron pipe forty millimetres in diameter and 3 to 3.2 metres long. One pipe could enclose as many as two hundred insulated conductors made of copper wire 0.3 to 0.4 millimetre in diameter. All space left free between the core and the pipe walls and also inside the core was then filled full with paraffin oil through a Tee-piece. The required oil level in the cable was maintained with the aid of oil tanks set up at elevated points along the line and joined to the cable by vertical stubs. This arrangement was not unlike the one used on oil-filled power cables for 110 or 220 kilovolts even today.

This other process used a different and, as we believe, a more elaborate way to keep out moisture – by a liquid rather than a solid filler. Lead pipes were abandoned because lead is too soft and has a low mechanical strength.

In 1880, the first attempt was made to dry the fibrous insulation for conductors in a vacuum rather than at atmospheric pressure.

The next step that moved telephone cables farther apart from their telegraph counterparts was made when it was proposed to maintain the cable filler at a positive pressure, using air or some gas instead of oil. The idea was that, should any of the joints develop a crack, the compressed gas would serve as a barrier to ingress of moisture. Jumping ahead, it may be noted that this idea is still used in present-day telephone cables.

Much as many writers have borrowed their ideas from the Bible created at the dawn of our civilization, so quite a number of ideas for present-day communication cables can be traced back to the dawn of the cable-making art.

The idea to use air was perhaps a decisive step in the advance of cable-making. Telegraph cables had a very high

capacitance – around two hundred nanofarads per kilometre (or two ten-millionths of a farad per kilometre) because their impregnated cotton insulation had a high relative permittivity ($\varepsilon_r \geqslant 4$). As will be recalled, C is directly proportional to ε_r. The high capacitance led to a high attenuation in cable circuits – a factor which substantially limited the range of telephone communication. This range could, in the circumstances, only be increased by using conductors of a larger diameter. On the other hand, air was known to have the lowest relative permittivity of all dielectrics: its ε_r is unity. (For those especially punctilious, it may be added that $\varepsilon_r = 1.000594$ at zero degrees Celsius and 760 millimetres of mercury.)

Telephone cable design and manufacture in the 1880s. In 1882 it was proposed to include air in the insulation of cable conductors. This somewhat reduced the capacitance of cables. Over each conductor was wound a helix of cotton string – twisted strands of cotton yarn. On top of it was applied, also in a helical pattern, the lapping of water-proof, latex-impregnated paper tape. That was the birth of present-day paper string-tape insulation.

Cable engineers were slow in adopting air instead of paraffin wax as a moisture-protecting filler. At first, attempts were made to use some sort of hybrid. One such hybrid appeared when in 1884 molten paraffin wax was pumped into the lead pipe enclosing cable conductors along with compressed gas. On turning solid, the paraffin wax became highly porous with the result that the cable capacitance was cut by about fifteen per cent. In a way, this was the forerunner of the foamed (or expanded) polyethylene insulation used today. Again, the pipe was made of lead, not pure, but in an alloy with zinc added to improve mechanical strength. The first seven kilometres of the new cable with three to seventy-five conductors 0.4 and 0.9 millimetre in diameter were buried in the ground, laid at the bottom of a river, and strung on poles in 1885.

As has been noted, the early telephone circuits were of the single-wire type, with the ground used as the return path to complete each circuit. They were unbalanced circuits, as communications engineers say. Lack of balance caused a resultant coupling with other circuits (through the ground) so that conversations on adjacent lines could be heard – a phenomenon known as cross-talk. To avoid it, a proposal was made in 1880 to use balanced circuits – those made up each of two conductors. The first design in which the two conductors were twisted together was proposed in 1881. But it was not a twisted pair, or twin. Rather, one conductor was wound along a spiral around the other. To avoid the difference in resistance between the two conductors, the straight wire would exchange places (be transposed) with the helical wire at each joint. It was not until 1882 that the conductors came to be twisted pairwise to make twins in much the same way as we do today. An international agreement to use two-wire telephone circuits was adopted at the Second International Congress of Electricians held in Paris in 1889.

Special mention should be made of the elegant design patented by S. F. Shelburne of the United States in 1886. In his scheme, known as the quad, four conductors are twisted together, but circuits are composed of the diagonally opposite, rather than adjacent, conductors lying at the corners of the square thus formed. To give full credit to Shelburne's invention, recall that the capacitance of a flat and a tubular capacitor decreases with increasing distance between its plates. A two-wire circuit may be viewed as a capacitor in which the plates are the two conductors. The capacitance of such a circuit in a cable is

$$C = (\varepsilon_r \times 10^{-6})/[36 \ln(2a/d_0)\psi] \text{ F/km}$$

where:

d_0 = diameter of the conductors

a = spacing between centres

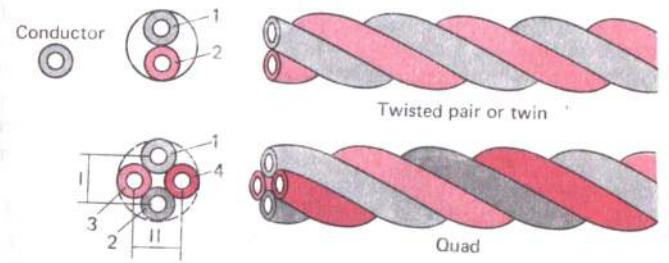


Fig. 5.14. Stranding of conductors in a cable

ψ = coefficient taking care of the effect produced by adjacent circuits

This equation was derived in 1938 by Professor V. Kuleshov of the Soviet Union.

Looking at Figure 5.14, it is seen that, given the same conductor design and dimensions, the spacing *a* between the diagonally opposite conductors, that is, *1* and *2*, *3* and *4*, that make up, respectively, circuit I and circuit II in a quad cable (as a cable consisting of four conductors is technically called) is greater by a factor of $2^{1/2} = 1.414$ than it is between the conductors in a twin. This produces what is known as the self-effect of a quad: Without any change in conductor design and without any increase in material requirements, the capacitance is reduced by ten to fifteen per cent, and so is the attenuation, solely owing to the manner of stranding. If we mentally draw diagonals between the conductors located at the opposite corners of a squad cable's cross-section, the drawing will look like a four-ray star. Quite aptly, cables with this type of stranding are known as star-quad cables throughout the world. The star-quad construction is the basic type used in present-day long-distance balanced communication cables.

Fig. 5.15. F. Borel, inventor of a press for application of lead sheath to cable

A major event in cable technology, whose significance can hardly be overestimated, happened when a press was invented for extruding a lead sheath over the cable core continuously advanced through the machine. The originator of the idea was a Swiss engineer, Dr. François Borel, and the first patent covering the lead extrusion press was granted to the French-Swiss firm of Berthoud & Borel in October 1879. However, the

lead press proved impractical – one charge of lead was barely enough to cover a relatively short length of cable; after the lead ingot had been used up, the sheathed length of cable had to be parted so that the next length could be worked. Still, it was an important step forward as compared with the cores drawn into pipes by hand.

In 1880-81, better press designs were proposed: one was a double-container horizontal press, and the other a single-container vertical press. Each could extrude the lead sheath over a complete delivery length of cable in a single run and had only to be stopped so that a fresh lead ingot could be charged. It would be no exaggeration to say that they were the forerunners of present-day lead and aluminium presses.

By 1885, a hydraulically operated, piston-type lead press had been finally developed and put into operation. Early in the same year, Werner von Siemens invented a cable armour made up of steel tapes. As he explained in his patent application, "Buried in the ground, a lead-sheathed cable must be protected against external damage, for example, due to heavy impacts with a sharp spade, for which purpose it is proposed that over the cable a helix of two relatively narrow steel tapes be wound, spaced about one-third of tape width apart, to be covered by the adjacent tape. With this form of application of armour tapes, the cable will retain a good measure of its flexibility".

All in all, there is every reason to say that the year 1885 marked the beginning of industrial cable manufacture and the advent of a true underground cable that had all the vital components: conductors, insulation (whatever the material), a moisture-proof lead sheath, and, where necessary, an armour for strength and protection. It had taken close on a half-century to produce the true cable. This is why, in contrast to the telegraph, the telephone and radio, we are hardly in a position to quote the exact date of its birth.

Telephone cable design and manufacture in the 1890s. Five

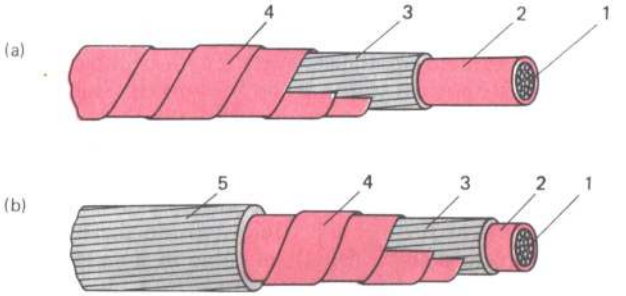


Fig. 5.16. Steel-tape armoured cable: (*a*) without and (*b*) with outer jute covering; *1*, cable core; *2*, lead sheath; *3*, armour bedding; *4*, armour; *5*, outer covering

years were to pass before cable designers came up with the 'right' insulation for telephone cables. The insulation proposed in 1882 consisted of cotton string whipping, air, and raw rubber-treated paper lapping – it was the paper that attracted the attention of cable manufacturers, and narrow paper tape soon hit the market. In 1886-1889, extensive tests (R & D work, we would say today) were carried out on conductors over which a helix of dry Manila paper tape lapping was wound.

Manila paper is made solely or mainly from fibres of tropical plants, Manila hemp and jute. It is dense, sturdy, and durable, and takes up moisture very little.

Now that the conductors were enclosed in a moisture-proof lead sheath, there was no need to impregnate the insulation or to fill the cable with paraffin wax so as to drive out moisture. With improvements in tape-winding machines, the paper lapping could now be wound away from the surface of the conductors, thus leaving an air space in between.

The first lead-sheathed cable with air-space (or dry-core) paper insulation was made in 1889, installed and handed over

for use in New York in 1890. From 1891 to the mid-twentieth century, dry-core paper insulation in many variants remained the only type of insulation used on communication cables. It is still in use, albeit on a smaller scale, even today.

The stand the makers of power cables take towards air is just opposite to that taken by the manufacturers of telephone cables. For power cables, air is enemy No. 1. A minute air bubble in the paper and, indeed, present-day polyethylene insulation of a power cable is a weak spot where ionization is likely to take place, to be followed by insulation break-down. That is why paper insulation for power cables is thoroughly dried and degassed under a high vacuum, and then pressure-impregnated to fill all the pores with a suitable compound.

For a communication cable, air is friend No. 1. As has been noted, air has a relative permittivity of unity, $\varepsilon_r = 1$. All cable insulating materials have a relative permittivity of two or more. For example, dry-core cable or thinner telephone cable paper has a relative permittivity of 2.0 to 2.2, and polyethylene, 2.2 to 2.3. The equivalent relative permittivity of an insulation made up of a solid dielectric (*d*) and air (*a*) is approximately equal to

$$\varepsilon_{r,eq} = \varepsilon_{rd} V_d + \varepsilon_{ra} V_a$$

where V_d and V_a are the fractions of the total volume of the composite insulation taken up by the solid dielectric and air, respectively.

It follows then that the equivalent permittivity is lower in cases where air takes up a greater proportion of the total volume. This reduction in the equivalent relative permittivity leads to a lower capacitance C, a smaller attenuation constant α, and a greater range l.

As a way of keeping noise out of the individual circuits, it was proposed to use shields. For the first time, the conductors of a telegraph cable insulated with gutta-percha and tarred cotton yarn were shielded in 1869. Wound over each conduc-

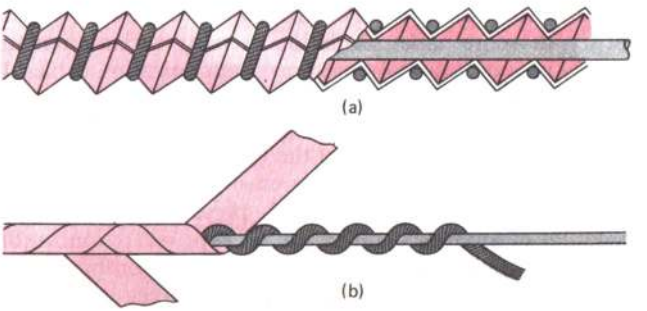


Fig. 5.17. Air-space insulation used in the 1890s: (*a*) balloon; (*b*) paper string whipping and tape lapping

tor was a helix of tin foil eight or nine millimetres wide. Unfortunately, tin foil was too weak and would often break as it was applied to a cable. To avoid this, it was proposed in 1892 to apply tin foil to a paper base. The shields used in present-day telephone cables use aluminium, rather than tin, foil 0.1 to 0.2 millimetre thick or cable paper metallized on one side.

The fact that air-space insulation had reduced the capacitance of cables to one-third of the former figure stimulated the search for better ways of applying it to conductors. In 1892, the first successful attempt was made to apply paper tape longitudinally rather than as a helix. A scroll-shaped die crimped it around the conductor to form triangles, and the edges were joined together by a box seam. In the cable first made in 1897, longitudinal paper tubes were formed by a crimping tool so that a corrugated paper helix was shaped around the conductor. Wound on the corrugated helix was a helix of binding string placed in the valleys of the corrugations. That was the 'balloon' type of insulation, but it didn't take root in cable technology.

For the same reason, an attempt failed in the 1950s to make polyethylene 'balloon' insulation held in place by a self-shrinking polyethylene string. On the other hand, the polyethylene 'balloon' insulation applied by extruding a hollow sleeve over the conductor and crimped to produce 'waists' spaced an equal distance apart along the cable has proved a success and is used in one type of long-distance communication cable. (That's another instance of feedback between product design and manufacturing process.)

The year 1892 saw the advent of paper-string insulation. Instead of cotton yarn, the string was made by twisting together paper strips (just 0.04 millimetre thick). An open helix of paper string was wound on the conductor, and on top of it was applied the lapping of two paper tapes laid up in opposite directions.

The cables made in the 1880s could carry each a limited number of circuits – fifty at most. The diameter of the conductors was increased from the original 'telegraph' figure of 0.3 or 0.4 millimetre to 1 or 1.5 millimetres. This was done to assure service to all the subscribers, no matter how far they were from their exchange.

In the 1890s, as more telephone sets were installed and

Table 6. Changes in the Urban Telephone Cables Used in the Late Nineteenth Century

Particulars	Year				
	1888	1892	1895	1896	1901
Max. number of two-wire circuits (pairs) per cable	50	100	150	200	400
Min. diameter of conductors, mm	1.0	0.9	0.9	0.9	0.64

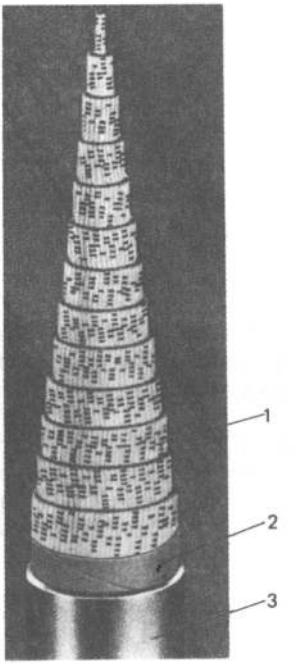


Fig. 5.18. 500-pair, concentric-layer air-space cable: *1*, cable core; *2*, paper core wrapping (or belt insulation); *3*, lead sheath

better cables were made, the number of circuits carried by a cable increased substantially. At the same time, there was a steady decrease in the minimal diameter of conductors.

As was the case earlier with telegraph cables, the pairs or the quads of a telephone cable were stranded together so that they were wound concentrically (or, rather, coaxially) on one another. This design which was the only one for all cables during decades and remains so in present-day long-distance

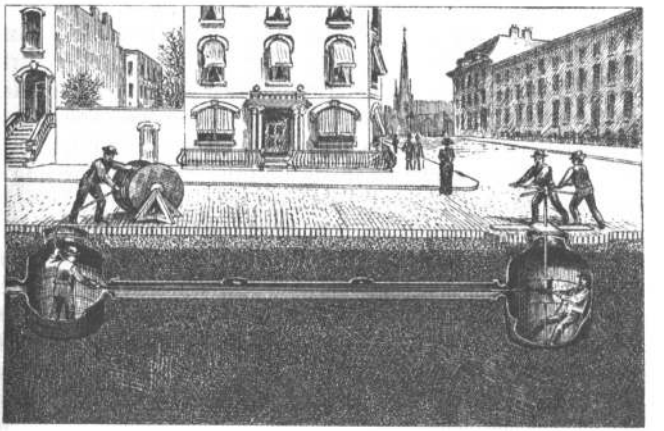


Fig. 5.19. Installation of a cable in a city conduit in the early twentieth century

cables is known as the concentric layer construction or formation. That is how the pairs are arranged in the layers of a cable (from centre towards periphery):

30-pair cable: $30 \times 2 = (4 + 10 + 16) \times 2$

100-pair cable: $100 \times 2 = (2 + 8 + 14 + 20 + 26 + 32) \times 2$

In the latter design, there are two spare pairs.

Thus, ingenious designs of telephone cables had been developed and industrial cable manufacture had been mastered by the beginning of the twentieth century. At that time, nearly two million telephone sets were in use and close on four and a half million kilometres of telephone wires and cables had been strung on poles and laid in the ground all over the world. Ten years later, in 1910, the figures were 10.4 million and 38.5 million, respectively.

Our story of the telephone cables used at the turn of the century would be incomplete if we failed to mention the

evolution of the lead sheath which protects the cable against moisture and chemical agents, and keeps out the stray electromagnetic fields set up by overhead power transmission lines, radio transmitters, and lightning discharges. The sheath is required to be flexible, to stand up well to cyclic bending, stretching and compressing loads, and the vibrations arising in transit and in service, and to resist corrosion well.

Unfortunately, lead has a low mechanical stress and stands up to vibrations poorly. To make up for these deficiencies, lead was alloyed with other metals. Historically, the first to be used as an alloying addition was tin: as much as one to three per cent tin came to be added to lead back in the 1880s. In 1900, it was proposed to alloy lead with 0.5 per cent antimony, and in 1912 with 0.8 to 1.2 per cent antimony. For one thing, this type of alloying was cheaper than three per cent tin. For another, the lead-antimony alloy was stronger mechanically and could be worked more readily.

Then came binary and ternary combinations of alloying additions, that is, those consisting of two or three components, such as cadmium, tin and/or antimony, bismuth and magnesium, bismuth and tin, bismuth and cadmium, or bismuth and antimony, with lead as the base. Later, tellurium, copper and arsenic came to be used as alloying additions.

Chapter Six

Cables in the City – Heaps of Problems

HOW MANY CABLES?

Suppose it has occurred to you to ring up a friend of yours. You pick up the receiver (or, rather, the handset into which both a transmitter and a receiver are built), and hear a continuous tone notifying you that you've been connected to the exchange. What you should do next and how you should converse over the phone is a very simple matter, known even to kids. But many of us, including the adults, do not know a thing about the path and the cables that the electric signals carrying our voices have to travel both ways.

Let's see how this is done in the USSR.

The handset is connected to the telephone instrument by a flexible three-wire cord. Running from the instrument to a fixture on a wall is a flexible two-wire cord, usually in a thin PVC sheath. The fixture on the wall is the start of what is technically known as a subscriber line or loop: a flat, two-conductor service wire is laid from the wall fixture to a ten-pair terminal box, *TB*, usually located outside your flat and attached to or sunk in the wall of your landing. The metal case of the terminal box encloses a plastic, trough-shaped connecting strip or block, sometimes called the plinth. Its front side carries ten pairs of brass terminal screws and each pair has a pair of contact pins on the rear side of the plinth.

Thus, as many as ten subscriber's wires from the telephone sets can be connected to one terminal box. A typical sixteen-storey point-block of one hundred and ten flats in the Soviet Union would have a total of eleven boxes, two boxes per three floors.

Running from the terminal boxes are ten-pair cables, not

wires. They may be installed on the walls of a block of flats or on vertical cableways built into the walls, and are carried to a distribution cabinet, *DC*. On their way to the cabinet, the ten-pair cables merge into cables with a greater number (but not more than a hundred) of pairs. These are subscriber distribution cables.

About two metres tall and usually painted gray, the distribution cabinets are inconspicuously installed (at least in the Soviet Union) in the entrance halls of buildings or outdoors, next to the walls. Sometimes, walking in the street you may happen to see a distribution cabinet open, with a man equipped with a handset or a circuit tester, doing something there. You may also happen to see that the cabinet is stuffed with wires strung between boxes at the top, middle and bottom of the enclosure. Each box encloses a set of ten plinths. Most often, the boxes at the top and bottom of the cabinet receive the distribution cables coming from terminal boxes, and the boxes at the middle are intended for the cables going to a local automatic telephone exchange or central office, *ATX*. They are called feeder cables.

In the Soviet Union, a typical local telephone exchange usually serves as many as ten thousand subscribers. Each of the feeder cables radiating from an exchange may have as many as a hundred to two or three thousand pairs. Along the route, the feeder cables again divide into smaller cables in which the number of pairs is a multiple of ten – these smaller cables are carried to subscriber distribution cabinets. The way all the cables and subscribers are served by a single local telephone exchange is shown in Figure 6.1.

A small Soviet community with less than ten thousand subscribers would usually have one telephone exchange housed, as a rule, in the same building with an automatic intercity telephone exchange or toll office. Each subscriber is assigned a four-digit number – this system of numbering is enough for as

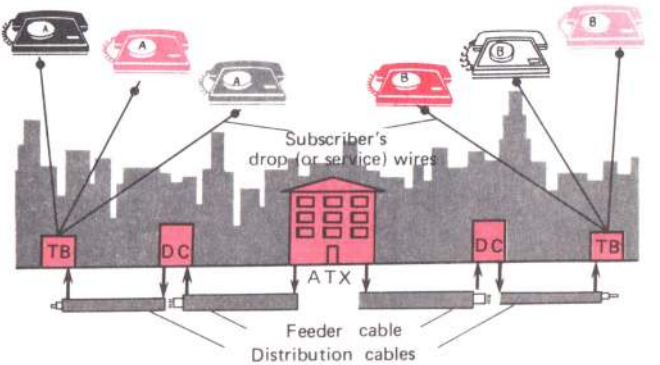


Fig. 6.1. Wires and cables linking subscribers served by a single automatic telephone exchange

many as $8 \times 1000 = 8000$ subscribers because the digit '8', when dialled first, will connect the calling party to the intercity exchange. Likewise, the digit '0', when dialled first, will connect him to one of the city's services: '02' to the police, '03' to the ambulance service, and '09' to the inquiry office.

Communities with eight to eighty thousand residents usually have several minor or local telephone exchanges. Each local exchange is connected to every of the other local exchanges by what is called 'direct hookup', using junction or interoffice trunk cables. In such cases, each subscriber is assigned a five-digit number, and each local exchange is directly connected to an intercity exchange by a line of its own.

Local (or minor) exchanges are connected with group exchanges, and these in turn with zone exchanges. The large zone exchanges are connected by trunk lines. A group exchange usually serves a hundred thousand subscribers, and a zone exchange a million subscribers. In networks with fewer than a million subscribers, each telephone set is assigned a

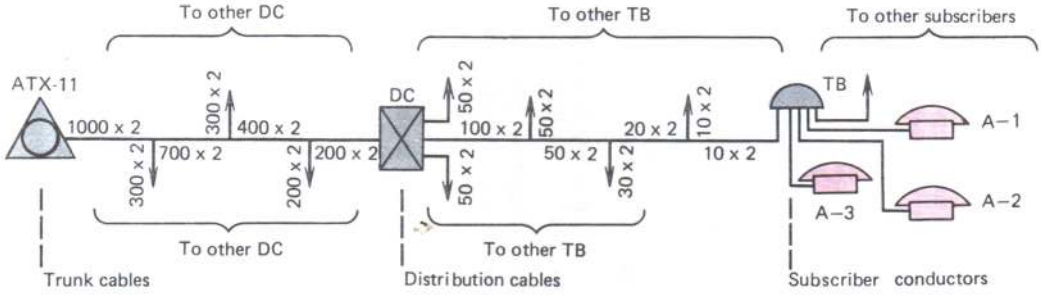


Fig. 6.2. Subscriber lines of a city telephone network

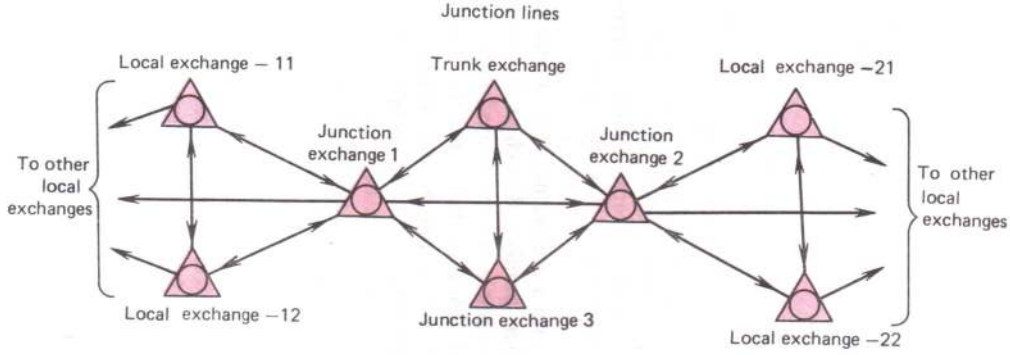


Fig. 6.3. Junction and trunk lines

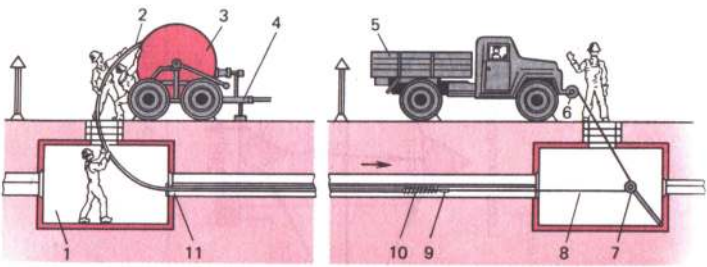


Fig. 6.4. Installation of a cable in a city conduit in the late twentieth century: *1*, manhole; *2*, cable; *3*, cable drum; *4*, cable trolley; *5*, cable machine; *6*, winch; *7*, pulley; *8*, rope; *9*, kink compensator; *10*, steel cable sleeve; *11*, safety sleeve

six-digit number; with a greater number of telephone sets, they are given seven-digit number. The digit dialled first identifies the desired one-million zone, the second indicates the desired hundred-thousand group in that zone, the third indicates the desired local (minor) exchange in that group, and the last four digits are the subscriber's number proper. Of course, other number schemes are in use in other countries.

It is common practice to install underground cables within the city limits in conduits which may be built of concrete, asbestos-cement, ceramics, or plastics and have ducts with a diameter of ten centimetres. So that it can readily be pulled through, the cable diameter should be not more than eight centimetres. Outside the city limits, cables are usually installed directly in trenches at least seventy centimetres deep, dug in the ground.

Let's trace the path travelled by signals during a conversation from subscriber No. 239-75-76 (the calling party) to subscriber No. 472-01-60 (the called party). The signal originates at telephone set No. 75-76 (these are the last four digits) and goes over the subscriber's loop, the subscriber distribution

and primary cables to local exchange No. 9 of group No. 3 in zone No. 2. Then it goes over an interoffice trunk or junction cable to group exchange No. 23 from which it is conveyed over another interoffice trunk cable to group exchange No. 47 (that is, group exchange No. 7 of zone No. 4), then over another interoffice trunk cable to local exchange No. 2 in group No. 7 and, finally, over a primary and a subscriber distribution cable and a subscriber's loop to telephone set No. 01-60.

Two women this author knows live on the same floor of the same block of flats, a mere fifteen metres from each other. But as chance has had it, their telephones are served by two different local exchanges, No. 207 and No. 208. Rather than to go and see each other, they feel like discussing things over the phone. The signals carrying their voices travel a path slightly shorter than we have just described, and then because their local exchanges fall in the same group service area.

With more than a total of three million telephones, Moscow ranks fifth in the world. It has (at this writing) over three hundred local exchanges organized into thirty group areas which are in turn arranged into six zones. All local exchanges are housed in standard buildings of dubious architectural virtues. The only pleasant exception is, in this author's opinion, the one built in 1904-1914. That's how it was described in the *Niva Magazine* for 1914: "The new telephone exchange, one of Moscow's magnificent edifices, is the last word of construction". It wouldn't be bad at all to read something like that about some of the new additions to the existing telephone exchanges some day.

To believe statistics, it takes from two to four thousand kilometres of two-wire cable circuits, or pairs, to serve one thousand subscribers. It is convenient to express the total length of circuits in terms of a fifty-pair cable designed by convention as a 50×2 cable. On average, cables carry three thousand pairs each. It follows then that sixty kilometres of

equivalent 50 × 2 cable would be required to interconnect one thousand telephone instruments.

Actually, the interconnections will use cables differing in the number of pairs they carry. Above all, there will be cables with as many as a thousand pairs (1000 × 2) and five hundred pairs (500 × 2), for which each kilometre is equal, in terms of the total length of pairs, to twenty and ten kilometres of equivalent 50 × 2 cable, respectively. Then there will be cables with twenty pairs (20 × 2) and ten pairs (10 × 2) for which each kilometre is equal to as little as 0.4 and 0.2 of a kilometre of equivalent 50 × 2 cable. Since in terms of the length of pairs, the multi-pair cables account for a greater proportion of the total figure, the actual length of installed cables is one-half to one-third of the length of equivalent 50 × 2 cable.

In the latter half of the 1980s, the number of telephones in use all over the world grew at a rate of 35 to 45 million a year. To support them, somewhere between 2.1 and 2.7 million kilometres of exchange cable, as expressed in terms of the 50 × 2 equivalent, had to be made.

City cables, also known as local or exchange-area cables, are the oldest among present-day communication cables – they have been the first to mark their 100th anniversary. Still, however paradoxically it may sound, more problems in their design and manufacture emerge every year than are solved. Let's dwell on some of them.

PROBLEM NO. 1 – WHICH METAL FOR THE CONDUCTORS?

Of course, this should be copper, silver would have been too expensive, the reader would, I bet, answer offhand, and he will be right. Conductors have been made of copper for over a century now. Still, copper is a scarce metal – it is not very

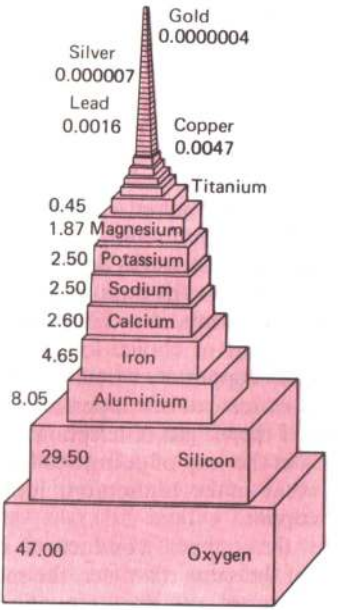


Fig. 6.5. Relative abundance of the basic chemical elements in the Earth's crust (per cent by weight)

abundant in nature. On the other hand, ever increasing quantities of telephone cables are manufactured.

The weight of copper wire that goes to make conductors depends on their diameter. The most commonly used diameters in the Soviet Union are anywhere between 0.32 and 0.7 mm, outside the Soviet Union also 0.8 mm and 0.9 mm. Let's take the most common one, 0.5 mm. The weight of the copper conductors in a cable carrying fifty pairs of conductors 0.5 mm in diameter (for which the shorthand notation is

$50 \times 2 \times 0.5$) will be 185 kilograms per kilometre run. Thus, nearly a half million tons of copper would be necessary to make two million and four hundred thousand kilometres – the average annual output of cables, which tends to increase with every year. That is a huge amount, and this explains why so much effort has been put into the search for a metal that could replace copper in cables.

Candidate No. 1 is aluminium. Incidentally, it was Oersted who obtained the metal aluminium for the first time. In terms of electrical conductivity it ranks fourth after silver, copper and gold. That is, if we take the base metals, aluminium is only second to copper. In nature, it is 1700 times more abundant than copper. The metal of choice for aircraft, aluminium is one-third as heavy as copper: its specific gravity is 2.7, and that of copper, 8.9. If used instead of copper, aluminium conductors would have reduced the weight of telephone cables appreciably. Then what stands in the way of doing so? Unfortunately, there are some 'buts' that make aluminium look not so well as compared with copper.

If we replace the copper conductors of a cable with aluminium wires of the same diameter, the resistance, R, of the circuit will rise 1.65 times, and the attenuation constant, α, will go up by a factor of $1.65^{1/2}$, or approximately 1.3. The increase of 1.65 times in the circuit resistance can be balanced out by increasing the conductor diameter, d_0, by a factor of 1.3. Then the aluminium conductors would be electrically equivalent to the copper ones. Unfortunately, the outside diameter of the cable would increase which is undesirable because the ducts in telephone conduits have a limited diameter. Also, more materials used to provide insulation, strength, and protection would be consumed.

Aluminium is markedly inferior to copper in tensile strength, ductility, and endurance (or fatigue). The tensile strength of soft aluminium wire is one-third of that of soft copper wire,

and its percent elongation is only a half as large. The number of bending cycles that will cause an aluminium wire to break is one-fourth to one-fifth of the number in the case of copper. Because of all these limitations, cables using aluminium conductors are far more difficult to make, notably to strand the conductors, to install an aluminium cable in a conduit, and to join delivery lengths end-to-end.

The worst drawback of aluminium, however, seems to be its poor resistance to corrosion, especially in the presence of moisture which can find its way into the cable through a damaged sheath or coupler. Should this happen, the aluminium conductors would be destroyed in part or completely in a very short time.

For decades have scientists and engineers in many countries been looking for ways and means of curing aluminium of its ailments. One way out, as has been found, is to use an aluminium alloy rather than pure aluminium. The alloying additions may be a half-percent each of iron, magnesium and silicon, sometimes also still smaller amounts of copper, zinc, and manganese. In terms of mechanical properties, aluminium-base alloys stand midway between copper and aluminium, but as to the electrical properties they are closer to aluminium. Unfortunately, aluminium-base alloys succumb to corrosion almost as readily as pure aluminium.

In recent years, attention has been drawn to aluminium wire clad with a coat of copper a mere ten to thirty micrometres (that is, 0.01 to 0.03 millimetre) thick. As to its properties, this copper-clad aluminium wire stands to copper closer than an aluminium-base alloy, but it is far more difficult to make. Should the copper cladding intended to protect the aluminium wire against corrosion develop even a minute flaw, the wire would corrode in the presence of moisture even more heavily than the plain aluminium conductor.

Since copper takes up a mere ten to fifteen per cent of the

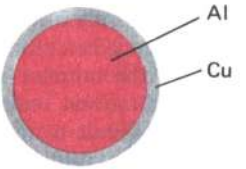


Fig. 6.6. Copper-clad aluminium wire

volume or cross-section of the copper-clad aluminium wire, the conductor's diameter is likewise greater than that of an equivalent copper wire by about twenty-three per cent.

An ingenious method has been developed in the Soviet Union for the manufacture of aluminium and copper-clad aluminium conductors so that the diameter of the product is increased only slightly. Let's put a question to ourselves: Is it really necessary for an aluminium conductor to be equivalent to a copper conductor in terms of resistance? For the quality of telephone transmission is decided by the attenuation constant of the circuit, and this constant (on neglecting L and G at voice frequencies) is mainly dependent on the product of R and C:

$$\alpha = (\omega CR/2)^{1/2}$$

It follows then, that in changing over from copper to aluminium or copper-clad aluminium conductors, the attenuation constant can be held at a constant value by suitably varying the R and C of the circuit. Notably, we can bring down R in comparison with its value of an equivalent copper wire and raise in proportion C, the capacitance which governs the thickness of the insulation (as the allowable capacitance increases, the insulation may be progressively thinner).

Since the value of R depends on the diameter d_0 of the conductor, and that of C on both d_0 and the diameter of the insulated conductor, d_1, we can relate these electric constants and design variables to one another, express d_1 as a function of

d_0, C, R, and α, and find the value of d_0 that would give the least value of d_1.

As this author has found, it is possible, in view of present-day insulation technology, to build an aluminium cable whose diameter would be by a mere eleven to sixteen per cent, rather than by twenty-eight to thirty per cent, greater than that of a copper cable equivalent in terms of attenuation. Thus, an aluminium conductor 0.64 millimetre in diameter with an insulation 0.32 millimetre thick (so that the insulated diameter is 1.28 millimetres) would be equivalent to a copper conductor a half-millimetre in diameter with an insulation a quarter of a millimetre thick (so that the insulated diameter is one millimetre). If, now, we increase the diameter of the aluminium conductor to three-quarters of a millimetre and reduce the thickness of the insulation to 0.18 millimetre, the insulated diameter will be just 1.11 millimetres. (This is an example of an unorthodox approach to a problem.)

The search for materials that could replace copper in cable conductors is still going on.

One day, when this author was on the staff of a research institute, he received a letter from a student of a vocational school. Earnest and thoughtful, the sixteen-year-old boy wrote that he was preoccupied with the saving of scarce metals, that he believed it vexing to see so much copper buried in ground where it was used so poorly, and that he proposed to replace the metal conductors in cables with water filling slim rubber or plastic tubes. Of course, water does conduct current, and the young innovator was right as far as that. But he overlooked a very important thing: the electrical conductivity of the 'most conductive' seawater is just four siemens per metre, which is as low as one fifteen-millionth of that of copper for which the figure is 5.8×10^7 siemens per kilometre. For a 'water conductor' to be equivalent to its copper counterpart electrically, its cross-sectional area would have to be increased in

proportion, and its diameter by nearly four thousand times. That is, instead of a copper conductor just a half-millimetre in diameter, we would have one with a diameter of two metres. That is, instead of the slim ten-pair distribution cable which we do not usually notice on our landing, we would have one the size of a three-storey house. The diameter of a thousand-pair cable would be the size of the Eiffel Tower.

PROBLEM NO. 2 – WHICH INSULATION?

The insulation in the form of a helix of paper strip wound over a conductor so as to form a tightly fitting tube, or technically, spiral strip paper insulation, dominated the field for about four decades. As cable manufacture was improved and expanded, it was only too natural for cable makers to try and increase the speed of the machines that applied paper insulation. Unfortunately, this could only be done to a certain limit above which the paper strip a mere 0.05 millimetre thick would break too often.

It is everybody's knowledge that paper is made from woodpulp, and this is prepared from wood, mostly coniferous. From a factory, the paper would go to cable works in rolls fifty to seventy centimetres long and sixty centimetres in diameter. At the cable works, the rolls would be slit by rotating disc knives into strips five to eight millimetres wide. Cheeses of strip would then be mounted on an insulating machine, and this would apply the strip to conductors.

"What if, instead of turning woodpulp into paper, slitting it to strips, and applying the strip to conductors, we apply the pulp directly?" This idea occurred in the early 1920s to a team of engineers at the Western Electric Company which was part

of the Bell System, USA. The idea finally matured to a commercial process for which six US patents were granted to six inventors on the same day of January 25, 1927. The patents covered, between them, a method for the insulation of conductors with pulp, a machine to do this, and the basic units of the machine. Among the six were John S. Little and Howard G. Walker who later became widely known for their publications. The commercial manufacture of cables using pulp insulation was launched in 1928. Three years later, the new process was disclosed in technical journals.

The American suit in the use of pulp insulation was followed by cable engineers in the Soviet Union. The Soviet pioneers were Efim Klibanov (later a State Prize laureate), Dionisy Ter-Mkrtchyan, and Nikolay Kuklin, three young engineers at Sevkabel, the country's oldest cable-making works. Apart from their desire and enthusiasm, they had very little on which to go: a hearsay about the American idea and a very brief, nearly cryptic article by H. G. Walker, which carried three or four nondescript photographs. That was the usual way for one company to hide its commercial secrets from others.

The motive power of the group was E. Klibanov (1897-1952). He took up a job at Sevkabel Works in 1925. In the next thirteen years, he rose from a technician to the Works' Chief Engineer. During the last eleven years of his life (from 1941 to 1952) he held the post of Chief Engineer at the Chief Administration for Cable Manufacture within the Ministry of Electrical Industry.

At first everything went on at a snail's pace. In the heat of the summer in 1933 Kuklin was paid a fee for one of his inventions. That was surely an occasion for a modest fête, and he invited his workmates to a small café. They sat down at a table near a window looking onto the Baltic Sea. Sitting there, they were engrossed in a talk about the new machine, the many bugs that were plaguing it, and the approaching

deadline. They were discussing a most troublesome unit which was to shape and polish the already applied insulation to the shape of a cylinder when a waitress came up to their table and uncorked a bottle of wine. Looking at how deftly she drove a corkscrew into the cork, Kuklin choked at a half-word: "Oh, boys! That's what we need! If we pass the conductor inside a corkscrew and rotate it fast, the screw would shape and work the insulation smooth".

His mates laughed off his idea and told him to use the corkscrew for what it was made. On the next day, however, Kuklin carried a drawing to the Machine Shop and before long a screw-shaped polishing tool spinning at three to six thousand revolutions per minute went to work.

That was another instance of what seemingly was a happy chance that set off a chain of thought. It was a repetition of what had happened in a Parisian café in 1876 when the talented Russian inventor P. Yablochkov, also waiting for a garçon in deep thought, took two long pencils out of his pocket and placed them in parallel on the table. The same instant it dawned upon him: "What if I place the carbons of an arc lamp exactly this way?" That was how, according to some sources, Yablochkov invented his 'electric candle' for which he took out a French patent on March 23, 1876.

To this we may add that in 1869 he had finished nine-month electrical classes for naval officers, had spent several years on theoretical and practical electricity as a member of a standing committee at the Polytechnic Museum's Department of Applied Physics and had worked in the workshop for physical instruments he had set up in Moscow. He had taken out several patents and had acquired a substantial knowledge (for his time, of course) in electrical engineering. Among other things, he was the first in the world to use, in 1874, his lamps to illuminate the railway track from a locomotive.

As the story goes, Sir Isaac Newton, when asked how he had

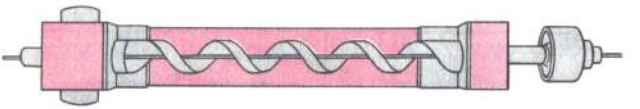


Fig. 6.7. Kuklin's screw-shaped polisher

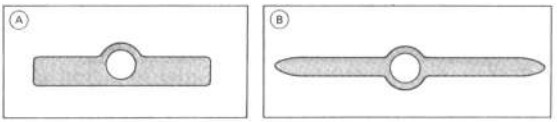
come upon his discovery of the law of universal gravitation, said: "I've been thinking of it". As simple as that!

The screw-shaped polishing tool invented by N. Kuklin (1897-1962) and called the Kuklin polisher for a long time has now been in service in the Soviet cable industry for over a half-century – an example of impressive longevity.

Kuklin took our USSR Inventor's Certificate No. 50919 dated July 22, 1936 for what he described as "a device to polish the insulating sheath". Four years later, on June 12, 1940, John N. Selvig, an American engineer, filed a patent application and, on March 2, 1943, took out US Patent No. 2312448, covering what he called "...a device for compacting and polishing material in strand form". In effect, Selvig's device was a modified embodiment of Kuklin's idea.

During the last years of his life, Kuklin worked in Moscow and Odessa. His biography was like one of those "fallen leaves of history", as V. Lidin put it, which his contemporaries have failed to preserve for future generations.

On November 7, 1933, the pulp-applying machine was put together. It only had six passes but it was followed by units with fourteen, twenty-eight and forty passes. Today, pulp-applying machines have sixty passes. Copper wires are fed from reels mounted on a pay-out stand, pass through a cleaner, and enter a tank enclosing a rotating perforated cylinder. There is a pipe which continuously fills the tank with pulp – a suspension of wood shredded to fibres as small as one or two millimetres and treated to leave as little as 0.1 per cent of impurities. As the wires move over the perforated cylinder,



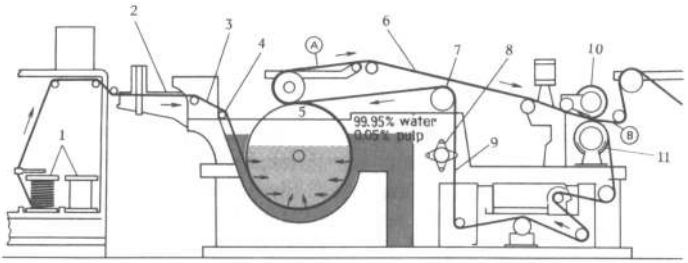
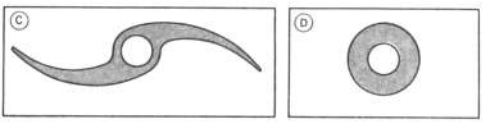
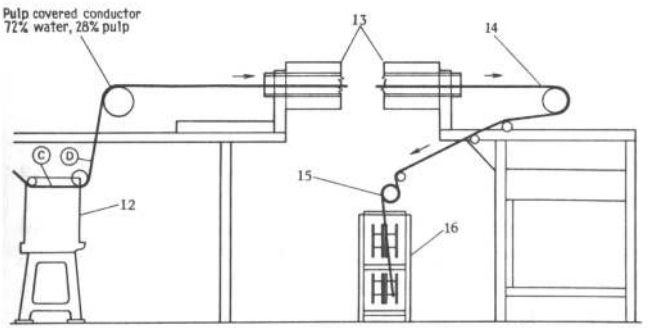


Fig. 6.8. Pulp-insulating machine: *1*, bare wire supply reels; *2*, electrolytic wire cleaner; *3*, bare copper conductor; *4*, finger roll; *5*, cylinder mould; *6*, pulp covered copper conductor on conveyor belt; *7*, vacuum

pulp lodges on them as a shapeless mass. Then the pulp-covered wires are passed through presses to squeeze a good deal of moisture out of the pulp which is given a true cylindrical shape by the Kuklin polisher. On leaving the paint pots, the insulated conductors pass through an electric drying oven and are carried by traction devices onto a take-up stand. The temperature in the drying furnace is 650-800°C, so that the moisture trapped in the raw insulation is rapidly raised to a boil and driven off. As the steam escapes, it leaves in the pulp coating a multitude of minute pores filled with air which, as we have learned, is highly desirable and, indeed, essential as a way of bringing down the capacitance of a cable.





roll; *8*, felt beater; *9*, felt belt; *10*, press roll; *11*, belt drive roll; *12*, polishing machine; *13*, drying furnace; *14*, pulling capstan; *15*, tension compensator; *16*, dual take-up reels

The next in the order of time, but the first in importance for exchange-area telephone cables has been continuous polyethylene insulation. In 1884, G. Gustavsson, a chemist in Russian service, polymerized ethylene, an unsaturated hydrocarbon answering the chemical formula C_2H_4, to produce a thick liquid not unlike lubricating oil. It was not until a half-century later, however, that Faucett and Gibson in Britain, and Dintses in the Soviet Union obtained, independently of each other, solid high polymers of ethylene for the first time. Large-scale commercial manufacture of polyethylene began in the 1940s, but the first kilometre of underwater communication cable (with an insulation consisting of one part

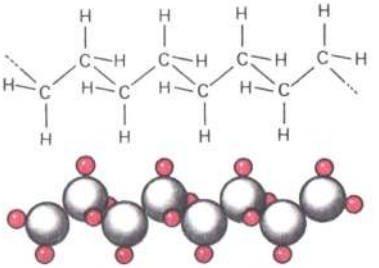


Fig. 6.9. Molecule of polyethylene

polyethylene and one part polyisobutylene) was made in Britain in 1939.

The happy union of excellent electrical, physico-mechanical and chemical properties has won polyethylene by far the largest field of application of all plastics in cable technology. A truly large-scale use of polyethylene as the insulation for exchange-area cables began in the 1950s, shattering the monopoly of pulp insulation. The advent of polyethylene insulation ushered in a new age in the technology of communication (and not only communication) cables.

What especially sets polyethylene insulation apart from paper-tube and pulp insulation is the fact that it does not take in moisture. In contrast, paper insulation would absorb water like the wick of an oil-lamp. Because of this, it has always had to be protected by a water-impervious metal sheath. Before the 1950s, the only material used as cable sheathing was lead, but this metal is even less abundant than copper, while as much as seven hundred kilograms or so has to be used to make one kilometre of cable – this is one and a half to four times as much as the consumption of copper.

With the advent of nonhygroscopic polyethylene insulation, there was no need any longer to use a lead sheath, mandatory

with paper insulation – now its job could be done well by a plastic or even polyethylene jacket. Indeed, more than a half of telephone exchange-area cables the world over today use polyethylene as both conductor insulation and cable sheath.

As a saying goes, happiness is never complete. As has been pointed out, a major advantage of spiral strip paper and pulp insulation is the entrapped air, which is why it is collectively called air-space (or dry-core) insulation. Its equivalent relative permittivity is 1.5 to 1.7. Alas, continuous polyethylene insulation has a greater figure of 1.9 to 2.1. (Polyethylene proper has a relative permittivity of 2.2 or 2.3, but the equivalent figure for the insulation is lower owing to the air enclosed between the stranded conductors of the cable.) Because of this, there is an increase in the effective capacitance of continuous polyethylene insulation as compared with the dry-core type and, as a consequence, an increase in cable attenuation. The effective capacitance could have been held constant by making the insulation a bit thicker, but this would have meant a larger cable diameter.

The conflict has been resolved by foamed or expanded polyethylene insulation. It is made by adding grains of some foaming agent to the polyethylene stock as it is applied onto conductors in an extruder. On reaching the extruder head where the temperature is 200-230°C, the foaming agent decomposes under heat and releases large volumes of volatile components. As a result, isolated voids measuring from twenty to a hundred micrometres across are formed. This is not unlike the porous paraffin-wax filler used in cables in the 1870s and the 1880s.

Owing to the air trapped in the pores, foamed polyethylene insulation is as good as air-space insulation in terms of electric properties and design, but.... Few inventions are free from any 'buts'. Advances in the insulation for city telephone cables have always posed more problems than they could solve – it has

been a sort of an endless chain: every new link included in it would call for yet another to be added.

As compared with continuous insulation, the three 'buts' of foamed polyethylene are an increased tendency to pick up moisture to a point where the material can well lose all of its electric insulating properties, a decreased dielectric strength, and a lower mechanical strength.

Going back to the 'chain' analogy, we can place the air-space insulation at the start, with the continuous insulation coming next, and with the foamed material following it. Obviously, there is a need for yet another link in the chain – one that would keep out atmospheric moisture. This link is a moisture-repelling filler.

In 1964, George A. Dodd of Britain came up with the idea of filling the free space of a cable, which accounts for about forty per cent of the total core volume, with a compound based on petrolatum, or petroleum jelly, an oil-refinery product which is a mixture of microcrystalline paraffins and oils. Dodd was granted the first patent for his invention on June 16, 1965. It seldom happens that the technical community accepts an innovation so unanimously as it did in the case of Dodd's filler. Before long, 'filled', 'fully filled', 'water-proof' and 'hermetically sealed' cables became a fact of routine cable practice.

Everything had, it would seem, been settled, but.... Experience with filled cables soon showed that although the petrolatum reliably kept moisture out of the cable, it tended to enter the pores and react with the foamed polyethylene. Inevitably, the performance of the insulation was degraded, and it aged prematurely. Was there a way out?

In the early 1970s, Canadian cable engineers proposed the use of a combination of foamed and continuous materials for insulation. As they argued, the inner foamed layer taking up eighty per cent of the total thickness would supply a sufficiently low permittivity. The thin outer layer was to act as a

barrier between the filler and the inner foamed insulation. Everything seemed to be clear as regards the cable design. But there were manufacturing aspects to be reckoned with as well.

I recall a session at an R&D board where a field engineer exclaimed passionately: "I don't know of a design that couldn't be made readily producible!" The answer was a burst of laughter from the manufacturing members of the Board. In their opinion, the view like that could only be held by a man who had never made even a short piece of cable. For a cable design might look perfect and well proportioned in a drawing, but it can be turned into a product with difficulty, by an awkward manufacturing process, and still it would not look a bit like it did in the drawing.

People who have happened to work under S. Ilyushin, an outstanding Soviet aircraft designer, recall his dictum: "Before you turn in your drawing, consult those who will translate it into the product. Even then, don't wait for an invitation to the Production Department – go there on your own and take a look at the product. After you've taken a look, touch it. After you've touched it, tug at it. If you happen to see you've missed at something, have enough courage to admit the fact".

Of course, it is far more difficult to apply a composite insulation with a thin outer layer than a single one. Technically, the problem can be solved in more than one way. One is to place two extruders in tandem, with the first applying foamed polyethylene, and the second the continuous material. Another is to use a single V- or L-shaped extruder in which one cylinder feeds foamed polyethylene and another the continuous material into a common mould head. The second approach seems to be more complicated, but it, too, offers a solution.

Thus, cable makers have at their disposal several types of insulation. But again the same question arises – Which insulation to use?

PROBLEM NO. 3 – THE VICIOUS CIRCLE

The type of insulation a cable maker chooses has a vital bearing on the type of sheath to be used. In turn, the type of sheath decides the type of insulation. What we have is a sort of vicious circle. Let's try and break it.

Attempts to do away with the scarce lead sheath were first made in the late 1930s and during the 1940s. Several materials were tried as lead substitutes, among them polyvinyl chloride, or PVC for short – one of the earliest commercial plastics. Unfortunately, so long as the conductors went on using air-space insulation, no one type of sheath, even multilayer, made up of alternating plies of PVC tubing, aluminium tape, and binding compounds, was able to keep atmospheric moisture out of the cable and to protect the insulation against moisture pick-up.

The advent of polyethylene insulation solved the problem. In 1948, the market was hit by cables enclosed in a sheath which bore the rather intriguing name of *ALPETH*, but the acronym simply stood for 'ALuminium + PolyETHylene', and the sheath design was the simplicity itself. In fact, it was a combination of two distinct cable elements: an aluminium shield and a simple extruded polyethylene sheath.

This combination of a polyethylene sheath, polyethylene insulation and an aluminium shield has now come to be the basic, classic design of present-day city telephone cables. PVC shielding and, sometimes, PVC insulation are now only used in cables installed in locations where fire hazard is high, such as in telephone exchange buildings. In contrast to polyethylene, PVC will not sustain combustion.

The shield is placed around devices or circuits to reduce the interfering or even damaging effect of the extraneous electromagnetic fields that might be set up by power transmission lines, the overhead contact lines of railways using alternating current for traction, and high-power radio transmitters.

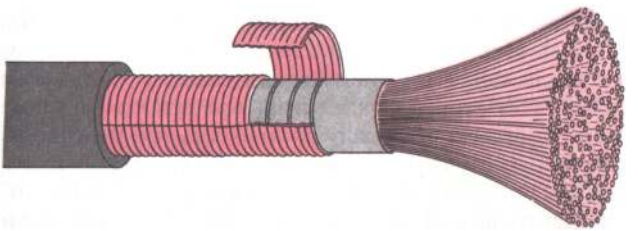


Fig. 6.10. Local telephone cable using polyethylene insulation, longitudinal aluminium shield, and polyethylene sheath

The aluminium shield in 'plastic' cables, too, was of an entirely new design, and it was applied by an entirely new process. The aluminium shield was made of aluminium tape 0.2 millimetre thick, smooth when used on the finest cables and with minute transverse corrugations when used on all cables more than fifteen millimetres in core diameter. The tape was applied longitudinally, rather than helically, with an overlap five to eight millimetres.

Although it is simple in design and to apply, plastic sheathing compares unfavourably with metal sheathing in the key effect – protection against moisture ingress. Water vapour can readily find its way (or 'diffuse', as scientists put it) through the sheath inside the cable – in full compliance with the diffusion laws established by Professor Adolf Fick (1829-1901) at Zürich University in 1855.

According to Fick's laws, if the water vapour content and, in consequence, pressure in the surroundings (which may be the atmosphere or the ground) are higher than they are inside the cable (which is very often the case because cables are manufactured in dry indoor locations), the vapour will inevitably tend to pass through the sheath from the medium with more vapour to the medium with less vapour, that is, inside the cable.

How fast the water vapour can pass through and, as a result, how much of it will finally find itself inside the cable depends on what is called the moisture permeability of the sheath material. This property varies from one material to another. Metals let through practically no moisture, and their moisture permeability ratio is 10^{-25} kg m m^{-2} s^{-1} Pa^{-1}. The figure for plastics is thousands of millions of times greater, being 10^{-16} for polyethylene and 10^{-14} to 10^{-15} for PVC. This explains, among other things, why cables having a polyethylene sheath are more preferable than those with a PVC sheath for outdoor installation.

Unquestionably, a very elegant and ingenious engineering feat has been accomplished by the laminated metal-plastic (mostly, aluminium-polyethylene) sheath, widely known as the Glover barrier after the British engineer D. W. Glover who patented it in 1961. His invention is a combination of a polyethylene sheath and an aluminium shield. In contrast to Dodd's invention, however, polyethylene is applied as a thin coat (0.02 to 0.03 millimetre thick) to one or both sides of aluminium tape. The shield laminated with polyethylene on only one side is applied to the cable core so that the polyethylene is on the outside. In an extruder, polyethylene is squeezed over the shield at a temperature of 200-230°C, which is high enough for the sheath to be welded to the polyethylene coating with the result that the shield is metallized on the inside. Its thin inner layer of metal acts as a barrier for water vapour tending to find its way through the polyethylene inside the cable.

The design has proved highly effective and readily producible. The shield made up of longitudinal tape and the extruded polyethylene coating are applied during a single manufacturing operation. For the water vapour that does pass through the polyethylene and 'bumps' into the aluminium barrier there remains only one passage between the over-

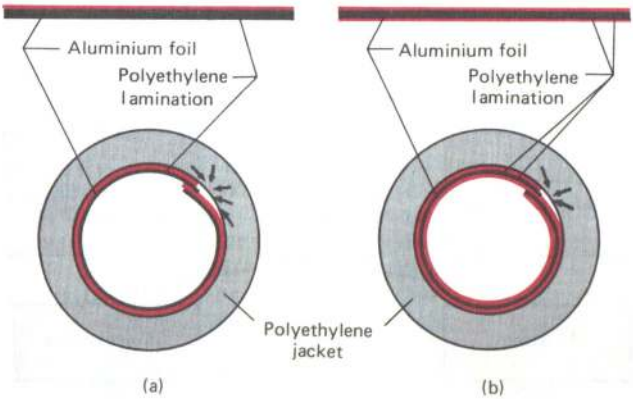


Fig. 6.11. Polyethylene-laminated aluminium sheaths using (*a*) two layers and (*b*) three layers of shielding tapes

lapping edges of the shield tape. When the aluminium is polymer-laminated on one side only, the rate of diffusion is, on average, one-hundredth of what it is in the case of the conventional polyethylene sheath. The double-sided lamination is far more effective because the polyethylene coats at the edges of the lap joints are welded together, and water vapour has now to penetrate a continuous polyethylene coat. Now the rate of diffusion is slowed down by a factor ten to fifteen thousand (!). This is the reason why the Glover barrier is so popular in literally all countries and undoubtedly outperforms any other types of polyethylene sheathing in existence.

The moisture-repelling filler and the aluminium-polyethylene sheath have substantially improved the reliability and service life of 'plastic' cables.

We have taken up a combination of plastic or metal-plastic sheathing and polyethylene insulation (continuous, foamed, or both). It would be a bit risky to combine the same sort of

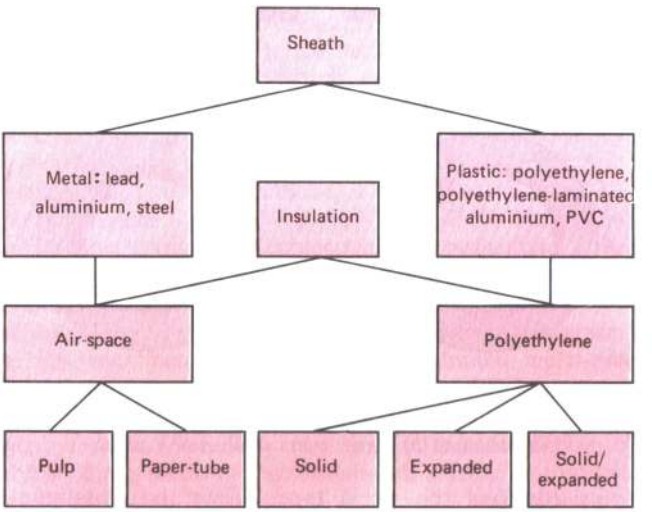


Fig. 6.12. Likely combinations of insulation and sheathing in local telephone cables

sheathing with air-space insulation – some moisture would be able to pass through all the same. Risky as it is, the idea seems very attractive, and cable engineers are currently working on it. Research carried out, first in Britain, then in France and Australia, have shown encouraging results. Some makers advertise 'off-the-shelf' cables that use air-space insulation and aluminium-polyethylene sheathing. Given the same working capacitance, such cables have diameters and weights by an average of ten per cent smaller than cables using polyethylene insulation. Still, air-space insulation can best be protected against moisture by a metal sheath. Not necessarily made of lead – it may be steel or aluminium.

The cable core design has been developing towards an

Table 7. Changes in the Design of Telephone Cable Core

Year	Maximum number of pairs	Conductor diameter, mm	Method of stranding
1901	400	0.64	Concentric layer
1902	600	0.64	Same
1910	900	0.64	Same
1912	1200	0.50	Same
1928	1800	0.40	Unit
1932	2400	0.40	Same
1961	3600	0.32	Same

increase in the maximum number of pairs and a decrease in conductor diameter. This is clearly seen from Table 7 which covers the period between 1901 and 1961.

In the past, telephone cables were mainly of concentric layer construction. Today, nearly all countries have changed over to the unit method of stranding. Stranding is a multistep operation. At first, conductors are twisted into elementary units (consisting of ten pairs or five quads in the USSR and some European countries). They provide as many circuits as there are terminals in terminal boxes. The elementary units are then assembled into subscriber distribution or secondary cables each providing from ten to one hundred pairs. In the case of junction or trunk cables with as many as one hundred pairs or more, the elementary units are first stranded into major bundles each consisting of fifty to a hundred pairs (twenty-five or fifty quads, respectively). Then the major bundles are assembled in an appropriate manner to form the cable core so that the required number of 100-pair units can be branched off a telephone line to distribution cabinets.

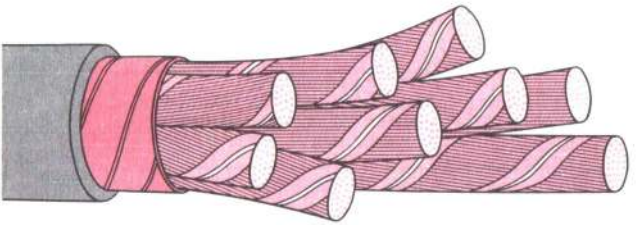


Fig. 6.13. Pulp-insulated, lead-sheathed local telephone cable of unit construction

In France, elementary units consist each of seven quads (7×4) and major units are made up each of twenty-eight quads (28×4) and fifty-six quads (56×4), or, which is the same, they are assembled from four or eight elementary units. In the United States, the cable core is assembled in three steps, using so-called sub-units of eight, nine, twelve, and thirteen pairs each. Now an elementary unit has twenty-five pairs and its formation is $8 \times 2 + 8 \times 2 + 9 \times 2$. A suitable colour scheme has been adopted for the insulation to identify any one of the twenty-five pairs in an elementary unit. Major units, of fifty pairs each, are assembled from either six sub-units, in which case their formula is $4 \times (8 \times 2) + 2 \times (9 \times 2)$, or from four sub-units, in which case their formula is $2 \times (12 \times 2) + + 2 \times (13 \times 2)$. Major 100-pair units are assembled from twenty-five-pair elementary units.

What are called SZ-stranding machines of ingenious design combine two consecutive operations – the stranding of conductors into pairs and of the pairs into an elementary unit, or the stranding of elementary units and a major unit.

The key problem that faces telephone cable technology today is to find ways and means of saving materials, especially the scarce metals copper and lead, and also polyethylene. This is a crucial problem because city telephone cables fall in the

'voice frequency' class. Each telephone subscriber has to be alotted one physical two-wire circuit – a pair in a cable, over which signals are transmitted at frequencies in the range from 300 to 3400 hertz.

Sometimes it is practised to put two subscribers on the same physical two-wire circuit, but then they can use their telephones only in turn, which is an obvious inconvenience. Transmission of tens of telephone conversations over a single pair is mainly limited to interoffice trunks because this form of operation calls for special multichannel equipment to be set up at telephone exchanges. (This matter will be taken up later.) However, the interoffice trunks account for a mere twenty per cent of the total length of city telephone networks.

The promise of a radical solution to this problem is held by fibre optics or, more specifically, by what are differently called fibre-optic, optical fibre, fibre or optical cables.

Chapter Seven

The Land of El-Ef

What is meant is not a land of supernatural, mischevious little creatures called elfs. The title of the chapter refers to a domain ruled by quite tangible quantities. One is distance, or '*l*', and the other is frequency, or '*f*'. In the choice of this name the author has followed the suit of Professor G. Babat, a prominent Soviet scientist and, at the same time, a visionary, who has written a book, "The Land of Pi-Ef", where he describes the uses of electricity in industry and traces how the efficiency of electric plant depends on the power (*P*) and the frequency (*f*) used.

All of the history of wire communications may be imagined as man's conquest of the Land of *El-Ef*, that is, as his drive to span ever increasing distances and to use ever higher frequencies.

THE DRIVE FOR DISTANCE

Bell's first telephone could only operate over a distance of not more than a hundred metres. A major leap along the distance (*l*-) scale was made with the invention of a carbon microphone or transmitter by David Hughes (1831-1900), an American scientist of British birth, in 1878. His transmitter was in the form of a carbon rod which touched two carbon buttons. Later, other and better modifications using carbon granules were developed by E. Berliner and T. A. Edison in the United States and by M. Mahalsky and P. Golubitsky in Russia. For all advances, however, the telephone was recognized by experts at the Munich Electrical Exhibition in 1883 as capable of operating over distances not more than ten kilometres. This

pessimistic prediction was however refuted three years later. As the *Scientific American* reported in one of its January issues in 1886, the Telegraph Construction and Maintenance Company was carrying out an experiment on the Eastern coast of England. In this experiment which, in the magazine's opinion, was to have an important impact, an ordinary telephone cable was laid between the town of Walton-on-the-Naze and a lightship lying at anchor ten miles offshore, and the parties at both ends of the line could converse with each other at any time and in any weather – a thing thought impossible before. The experimentors maintained that the telephone could operate over a much longer distance.

A further increase in the distance spanned by the telephone came, among other things, with improvements in cable design, notably due to conductors of a larger diameter and air-space insulation of low capacitance.

For all improvements, however, telephone cables could only be used within city limits and suburbs until the early twentieth century. Intercity telephone services employed overhead lines built with copper wires three to five millimetres in diameter. This sort of line was set up between St. Petersburg and Moscow in Russia in 1898. It was the longest line of the time in Russia and among the longest in Europe.

Long-distance telephone cables became a fact of telephone practice in the wake of studies carried out by Professor Michael Idvorsky Pupin (1858-1935), an American electrician of Serbian origin. He invented a form of inductive loading which later came to be known as coil loading. He drew upon Heaviside's discovery that the loss of energy in a line could be minimized by artificially increasing its inductance so as to approach the ideal condition in which

$$R/L = G/C \text{ or } RC = LG$$

and which was dismissed by Heaviside's contemporaries as

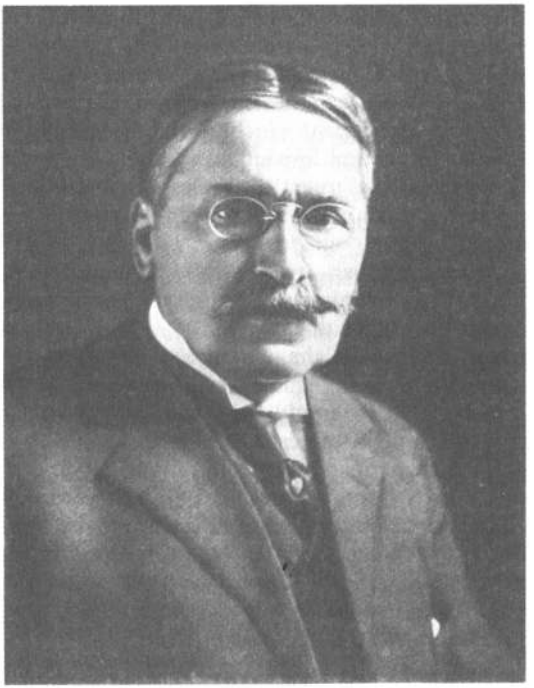


Fig. 7.1. Michael Idvorsky Pupin, American electrician of Serbian origin

something not worth attention. Pupin proposed to insert iron-cored loading (or Pupin) coils into telephone lines at regular intervals (called 'pupinized' lines for a long time) and computed the spacing between the coils. In this way, the inductance of the line can be raised tens or even hundreds of times, thus reducing the attenuation of the waves of speech current in the telephone circuit.

Some sources say that Pupin made his invention in 1900 or 1901. Actually, he took out his first U. S. patent in 1899.

Pupin's invention was first applied commercially in 1902 to the New York-Newark line sixteen kilometres long, which used a 200 × 2 × 0.9 cable. This opened up the way for the construction of long-distance or toll cable lines.

Loading coils increased the operating distance of telephone lines impressively – to thirty-two kilometres in 1903, seventy kilometres in 1904, and one hundred and forty-five kilometres in 1906. In all of those cases, the lines used twisted pair cables 1.3 to 1.6 millimetres in diameter.

Soon after Pupin's invention, Karl Krarup of Denmark came out with another ingenious way of artificially increasing the inductance of a cable line, called continuous loading. Rather than to insert loading coils in a telephone line every one and a half to two kilometres, he proposed to wind around the copper conductors of the cable a thin steel tape or wire 0.2 to 0.3 millimetre in diameter. The rationale of his invention was that steel has a permeability, μ, which is 100 to 200 times as great as that of copper, and inductance, as will be recalled, depends on permeability.

Continuous loading proved less efficient in increasing the operating distance of a line than coil loading. This was because the steel wrapping applied to the copper conductors increased the inductance of the circuit eight to ten-fold, as against the increase of fifty to seventy-five times produced by coil loading. But this drawback was more than offset by the fact that continuously loaded cables were more manageable for undersea laying. At the time of the invention, there was no way of laying a coil-loaded marine cable from a ship: the diameter of a Pupin coil was several times that of the cable; also, in contrast to the flexible cable, the coils were of rigid construction – in passing over the sheave of the cable-laying machine, the coil-loaded cable would break at the points where the loading

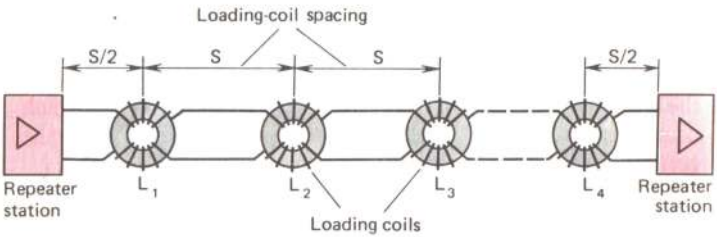


Fig. 7.2. Connection of loading coils into a cable circuit

coils were inserted. A continuously loaded cable, on the other hand, had the same diameter and the same flexibility everywhere along its length.

As an aside, the author recalls the 'behind-the-scene' disputes he once happened to hear taking place between R&D people and field engineers. The crucial question has always been: Who gives tangible benefits to society – science or engineering? The word 'tangible' would be strongly emphasized, and 'benefits' would usually mean an immediate payoff.

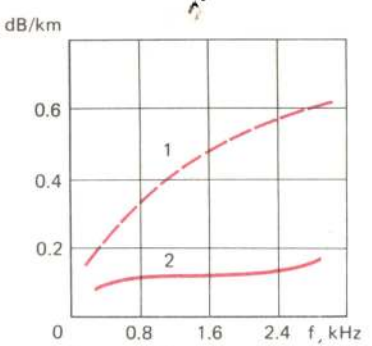


Fig. 7.3. Cable attenuation as a function of frequency: *1*, without coil loading; *2*, with coil loading

Those who favour the immediate payoff of engineering effort and set it against the 'no-money' equations and charts originating in scientists' study-rooms and labs seem to follow an old adage: A bird in the hand is worth two in the bush. Unfortunately, they overlook the fact that a single scientific discovery may well give rise to several engineering breakthroughs. It is highly doubtful if anyone could stick a price tag in roubles, dollars, francs, or marks to Heaviside's equation, Newton's binomial, or Fick's laws although they were all given high academic awards. In contrast, both coil and continuous loading had a money value, and a high one at that.

Thousands of cable lines throughout the world today are coil and/or continuously loaded. But they have become what they are because the impractical, other-worldly Heaviside once derived an equation that finally helped to increase the range of communication. Even decades later, his equation was a source of inspiration for engineering effort. In 1936, I. Koscheyev (1902-1965), a professor at the Moscow Institute of Telecommunications, came up with the idea of applying a thin coat of iron to the copper conductors of a cable electrolytically rather than as a continuous wrapping. In the 1940s and the 1950s, a good deal of experimental work was done in the manufacture of bimetallic cable conductors, but Koscheyev's idea was finally abandoned: by that time it had been found that any further increase in the inductance of a telephone line would stand in the way of mastering the Ef province of the Land of El-Ef, that is, operation at higher frequencies.

In the 1950s, cable engineers racked their brains a lot in order to find how plastic-sheathed cables filled with air at a positive pressure could be shipped, stored and operated in the same way as cables covered with a metal sheath impervious to moisture and air. They found an answer – and quite unexpectedly – in Fick's diffusion laws apparently as far from

Table 8. Maximum Distance of Telephone Communication

Line type	Copper conductor diameter, mm	Maximum distance of telephone communication, km	
		without coil loading	with coil loading
Overhead	4.0	500	1000
Cable	2.0	45	200
	1.3-1.4	30	130-140
	0.9	20	60-70

electrical engineering as anything and deduced near a century before.

The naiveté and oversimplification of a pragmatic approach to science has pointedly been criticized by the outstanding Soviet physicist P. Kapitsa: "It is perfectly clear that the new tools of human civilization, such as the dynamo and the telephone, could hardly have been invented without the fundamental research and discoveries made by Michael Faraday. It is likewise perfectly clear that it would have been a sheer folly to expect that Faraday should have made the dynamo and the telephone with his own hands".

The artificial increase in inductance has undoubtedly been an important milestone in the development of cable telephone lines. But the distance over which telephone communication is possible is limited even on coil-loaded lines.

A major improvement in the distance of telephone communication came with the advent of repeaters – a combination of apparatus for receiving either one-way or two-way communication signals and delivering corresponding signals that are either amplified or re-shaped or both. The key component of this apparatus is an amplifier.

In 1904, Sir John Ambrose Flemming (1849-1945), the first Professor of Electrical Engineering at University College, London, invented what he called the thermionic valve – a two-electrode electron tube now commonly called the vacuum diode. It has a cathode, or the negatively charged electrode, held incandescent by a current drawn from a battery, and an anode, or the positively charged electrode. The hot (or thermionic) cathode emits electrons, and these stream towards the anode, thus setting up an electric current inside the device. The Flemming valve could serve as a detector of radio signals, but it couldn't amplify them.

The first amplifying tube was invented by Lee De Forest (1873-1961), an American radio engineer, in 1906, who called his brainchild the Audion. He placed a third electrode (grid) into the two-element Flemming valve between its cathode and anode (or plate), for which reason the De Forest device is now known as the vacuum triode. The inventor was granted the patent on January 15, 1907. When an alternating current is applied to the grid, it boosts the electron stream inside the tube and, in consequence, the resultant anode (or plate) current during the positive half-cycles of grid current and suppresses it during the negative half-cycles. This changing anode current, when passed through a resistance external to the triode, generates a magnified copy of the voltage applied to the device; that is, amplification takes place. For this reason De Forest's tube came to be employed in all amplifiers, including telephone repeaters.

In a repeater, the electric signals generated during a telephone conversation are applied, after they have partly been weakened, or attenuated, in their travel along the line, to the grid. Acting as already explained, the grid voltage causes the anode current flowing inside the amplifier tube to grow in magnitude so that the resultant anode current is a magnified replica of the incoming signals. As they emerge from the

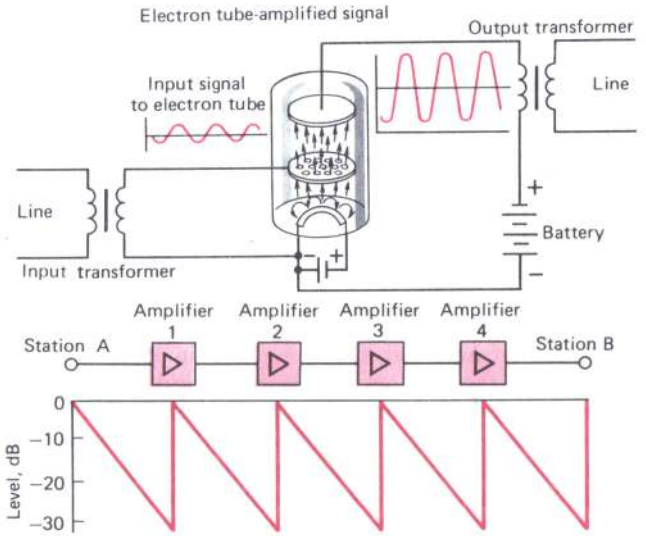


Fig. 7.4. The vacuum triode as an amplifier and the power levels of signals transmitted over a long-distance cable

repeater, the output signals entering the line have thus been restored in power.

It is easy to see that if we place several repeaters spaced a certain distance apart along a line, the total distance covered may be made as long as we may wish to.

Present-day telephone repeaters operate in much the same way as we have described, except that the vacuum tubes of the past have given way to transistors almost everywhere.

It has been internationally agreed to take a telephone transmitter output power of one milliwatt (or one thousandth of a watt) as a reference. In addition to attenuation, the loss of energy in a line as the signals travel along it may be ex-

pressed in terms of energy level. The zero, or datum, level is that existing at the start of a line and equal to

$$P_0 = 1 \text{ milliwatt} = 1 \times 10^{-3} \text{ watt}$$

At a point which is a distance l away from the start of the line, the power of the attenuated signal will have dropped to one microwatt, or one-millionth of a watt, and the energy level will be

$$-10 \log_{10}(P_0 / P_l) = -30 \text{ dB}$$

that is, thirty decibels down from the datum level. Suppose that the repeater installed at that point boosts the signal's power a thousand times. This means that the energy level will be raised by thirty decibels to become again equal to the datum level.

That is how repeaters restore the attenuated signals in power when a telephone conversation is transmitted from one point to another. It is usual to refer to the distance between two adjacent repeaters as a repeater hop or a repeater spacing. State-of-the-art repeaters can boost the power of signals from a thousand to a million times.

Practical use of repeaters in communication lines began in the second decade of the twentieth century. In 1913-1914, the United States built its first intercity cable line 730 kilometres long in which coil loading was happily combined with repeaters. The line used a $7 \times 4 \times 2.6 + 18 \times 4 \times 1.8 + + 6 \times 2 \times 1.8 + 18 \times 2 \times 1.3$ cable in which the pairs were placed between the quads.

For about twenty years, the repeater spacing ranged from seventy to one hundred and fifty kilometres, depending on the amount of inductive loading used.

In the Soviet Union, valuable contributions to the design and use of telephone repeaters were made by V. Kovalenkov (1884-1960), a prominent Soviet authority on wire communications, who received many academic and government awards.

UP THE FREQUENCY SCALE

Cables account for a major share of the metals and money put into any wire communication facility. It is not surprising therefore that every effort has been made throughout the history of line communications to use each physical circuit to the utmost. One example is the use, on telegraph lines, of ground or water as the return path instead of a second wire in a circuit.

The history of telegraphy has known several approaches to the transmission of two and more messages over the same wire, using direct-current pulses for the purpose. In 1881, G. Ignatyev (1846-1898), Captain of the Russian Army, devised a scheme in which telegraph signals were to be transmitted at frequencies from zero to a hundred hertz, and telephone signals at frequencies from 300 to 2700 hertz over the same wire and at the same time. Telegraph and telephone signals were to be separated by a combination of capacitors and inductors inserted in the circuit – a forerunner of what we call electric wave filters today. The inductors were to block the passage of telephone signals, and the capacitors, the passage of telegraph signals.

The idea suggested by Ignatyev was carried to practical use by another Russian inventor, E. Gvozdev (1847-1896), who was able to send both telegraph and telephone messages over the same circuit for a distance of three hundred kilometres.

In 1882, Frank Jackob demonstrated that each pair in a cable could provide two physical circuits and a third, or phantom, circuit through the use of suitable transformers. The name 'phantom' stresses the fact that this circuit does not exist physically. It is a superimposed circuit derived from two suitably arranged pairs of a cable, called side circuits. Each pair is a circuit itself and at the same time acts as one conductor of the phantom circuit. The use of phantom circuits

improves the handling capacity of a cable line by as much as fifty per cent.

For the first time experiments with phantom circuits in a cable were carried out in 1889 when a technique had been developed to make what are known as star-quad cables in which the individual conductors are first arranged in groups of four, each group is then insulated as a whole, and the four conductor units are held together round a central string to form a quad. In one quad the two conductors diagonally opposite to each other form a pair – they are used as the two conductors of one circuit.

In 1903, the German engineers Willhelm Dieselhorst and Arthur Martin proposed a cable construction different from star-quad cables. In their process, the individual conductors are likewise first arranged in groups of four, but each group is then twisted so as to make two pairs differing in twist length, that is, the length of cable in which the conductors make a complete twist round the core. The two pairs, or twins, are then stranded to form a quad. The engineers also designed and built a machine that could perform the two operations at the same time. This type of cable has come to be known as the DM type after its inventors. Sometimes, it is referred to as the 'multiple-twin' (MT) type.

The invention of the phantom circuit called for the development of suitable inductors so that phantom-circuit cables could properly be coil-loaded. In turn, the use of phantom circuit was made possible by the advent of quadded cables (star-quad and multiple-twin types) and this prompted a change-over to quadded cables for long-distance lines everywhere. The first coil-loaded DM-quad cable was installed on a ten-kilometre line in 1910. Beginning in 1911, most intercity cable trunks were designed with a view to using phantom circuits.

A real breakthrough in the utilization of communication

cables occurred with the invention of multichannel operation which offered an opportunity to use high-frequency (or a carrier-frequency) telephony. Curiously, a good deal of assistance in solving this problem of wire communication has been coming from radio engineering, its rival.

Several things need to be recalled and several facts refreshed for an insight into the principle of carrier-frequency multichannel telephony.

One fact is that the basic human speech sounds lie in the frequency range from 300 to 3400 hertz. Therefore, it is customary to assign an audio baseband of 0 to 4000 hertz, that is, 4 kilohertz, to each telephone conversation or, technically, to each telephone channel, the excess over the maximum 3400 hertz frequency being a guard band left vacant between two adjacent channels to safeguard against mutual interference. (It is to be noted that the word 'channel' may be used in several meanings. One refers to a portion of the frequency spectrum assigned to convey intelligence. Another refers to the assemblage of telephone exchange and line facilities providing for the transmission of signals between any two points.) How should we go about sending several telephone conversations over the same physical circuit (one pair of conductors)? Obviously, this cannot be done by lumping them all in the same audio baseband of 0 to 40 kilohertz for the simple reason that at the receiving end they will turn up as an unintelligible mixture.

To avoid this, two techniques have been developed. One is known as frequency division multiplex (abbreviated FDM), and the other is time division multiplex (abbreviated TDM). Let's dwell in more detail on FDM which was the first to be used commercially.

Suppose that we are to transmit three telephone conversations over the same pair of conductors, using the FDM technique. Each conversation is allocated an audio baseband of 0 to 4 kilohertz of its own. The three audio basebands are

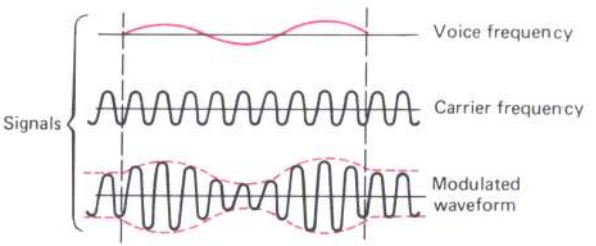


Fig. 7.5. Amplitude modulation

separately translated to a higher frequency band of the same 4-kilohertz width. This translation is known as modulation, and it is effected by three modulators, M, one for each channel. Each modulator receives its audio baseband extending between f_{min} and f_{max}, from a telephone transmitter, A, and also a so-called carrier frequency, f_i, from a carrier oscillator, one for each modulator. For example, modulator M_1 may use a carrier frequency $f_{c1} = 12$ kilohertz, modulator M_2 a carrier frequency $f_{c2} = 16$ kilohertz, and modulator M_3 a carrier frequency $f_{c3} = 20$ kilohertz. As is seen, the difference between adjacent carrier frequencies is 4 kilohertz as well. Each audio baseband is modulated upon the respective carrier frequency, and the process of modulation produces several resultant frequencies. The strongest of them are the carrier frequency f_i and the two sidebands, the lower sideband extending from $f_i - f_{max}$ to $f_i - f_{min}$, and the upper sideband extending from $f_i + f_{min}$ to $f_i + f_{max}$. Taking $f_{c1} = 12$ kilohertz as an example, the respective lower sideband will extend from 8600 to 11 700 hertz and the upper sideband from 12 300 to 15 400 hertz. The two sidebands are arranged symmetrically about their carrier and embody the same information about the signal waveform. Therefore, only one may be used for transmission, say, the

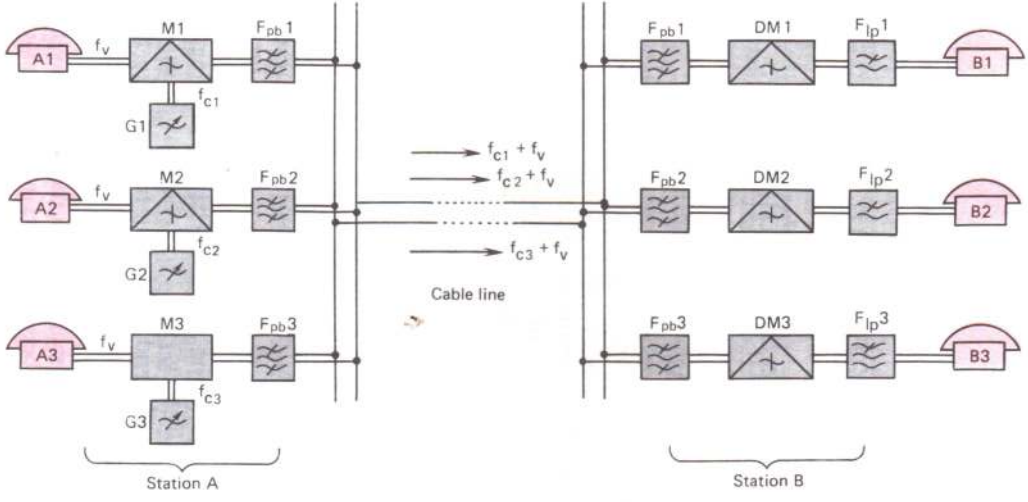


Fig. 7.6. Use of frequency division multiplexing for telephone transmission: *A*, subscriber; *M*, modulator; *DM*, demodulator; F_{pb}, bandpass filter; F_{lp}, low-pass filter; *G*, carrier generator; f_c, carrier frequency; f_v, voice frequency

upper sideband. The other, or lower, sideband will then be cut off by a bandpass filter.

The three carrier frequencies and their respective upper sidebands take up a frequency band $3 \times 4 = 12$ kilohertz wide, which extends in our example from 12 to 24 kilohertz. All of these frequencies can be transmitted together over a single pair of conductors.

Since each telephone conversation uses a high-frequency channel of its own (the first between 12 300 and 15 400 hertz with a carrier frequency $f_1 = 12$ kilohertz, the second between 16 300 and 19 400 hertz with a carrier frequency $f_2 = 16$ kilohertz, etc.), there is no mutual interference between them.

The human ear cannot respond to the high frequencies transmitted over the line. Therefore, there is a need to carry out a reverse operation at the receiving end, that is, to translate each of the high-frequency channels to the original audio basebands. This operation is known as demodulation and it is accomplished by devices called demodulators, *DM*. The signals sent out by a subscriber at point *A* are routed to the 'right' subscriber at point *B* via bandpass filters. Each will pass frequencies from the 'right' channel and block the frequencies from the 'wrong' channels. The signals appearing at the output of the demodulators are at audio frequencies. They are passed through low-pass filters and conveyed over three physical two-wire circuits to three telephone sets.

Multichannel telephone systems use various types of electric wave filters, all of them incorporating inductors and capacitors. The point is that an inductor of inductance L, when placed in an alternating-current circuit, presents varying opposition to the passage of current at different frequencies. A rise in frequency leads to an increase in the opposition, or inductive reactance, presented to the current:

$$X_L = \omega L = 2\pi f L$$

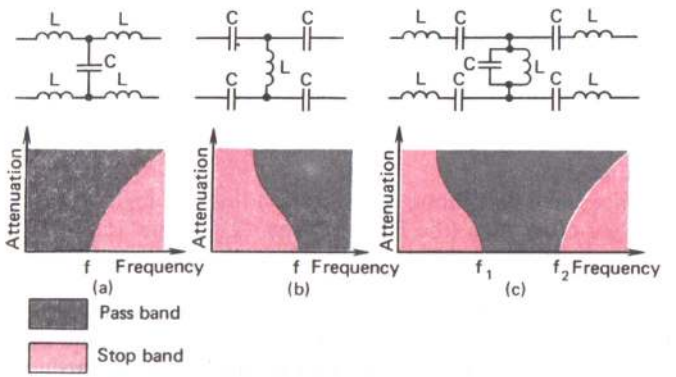


Fig. 7.7. Electric wave filters: (*a*) low-pass; (*b*) high-pass; (*c*) bandpass

That is, an inductor readily passes low frequencies and blocks high frequencies.

The effect that a capacitor of capacitance C produces in an alternating-current circuit is quite opposite: the capacitive reactance, or opposition, presented to the flow of current decreases with increasing frequency:

$$X_C = 1/\omega C = 1/2\pi fC$$

That is, a capacitor readily passes high frequencies and blocks low frequencies.

For the first time carrier-frequency telephony was put to practical use in 1930. Two channels were set up over a coil-loaded cable, one occupying a band of 300 to 2700 hertz and the other from 3500 to 5700 hertz. The ensuing success prompted the change-over to a four-channel, then to a twelve-channel and bigger systems.

As more telephone conversations were put on the same physical circuit, there was a steady decrease in the degree of

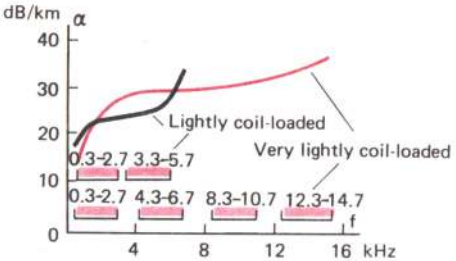


Fig. 7.8. Frequency spectra of early multichannel cable communication systems using light (*L*) and slight (*S*) degrees of coil loading

coil loading. The point is that a coil-loaded cable acts as a low-pass filter whose upper cutoff frequency, f_{co}, increases with decreasing inductance of the loading coils:

$$f_{co} = 1/2\pi (L_s C_s)^{1/2}$$

where the subscript '*s*' stands for a loading-coil section. Finally, coil loading was abandoned completely so that more channels could be derived on the same circuits.

Recent decades have seen an explosive growth in the use of the other form of multichannel operation based on time division multiplexing (TDM) and pulse-code modulation (abbreviated PCM). This is a form of pulsed modulation in which the signal is sampled periodically and each sample is quantized and transmitted as a digital binary code. Here, too, signals are transmitted over cable lines over a wide band of high frequencies.

It is a widely accepted fact that advances in one science usually owe a good deal to what has been achieved in adjacent fields. The advent of multichannel telephone systems has greatly influenced communication cable technology, including cable theory, design, manufacture, and operation.

Early in this century, only voice-frequency signals were

Table 9. Early Long-Distance (Toll) Cable Lines

Baseband, kHz	No. of channels	Repeater hop, km	Coil leading		Coil inductance, mH
			description	symbol	
0.3-2.7	1	140	Medium	M	140/56
0.3-5.7	2	70	Light	L	30/12
0.3-14.7	4	70	Slight	S	3.2/—
12-60	12	35	None	—	—

Note: The inductance figure in the numerator applies to the side circuits, and that in the denominator to the phantom circuit.

transmitted over all communication cables. In the mid-1930s, cables came to be classed into voice frequency and carrier-frequency types. In addition to the usual balanced cables, what are known today as coaxial cables made their appearance.

What's the difference between the two types of cable?

Suppose we have a line or circuit made up of two identical conductors: they have the same diameter, use the same type and thickness of insulation, and are arranged so that a plane of symmetry may be passed between them in any transverse

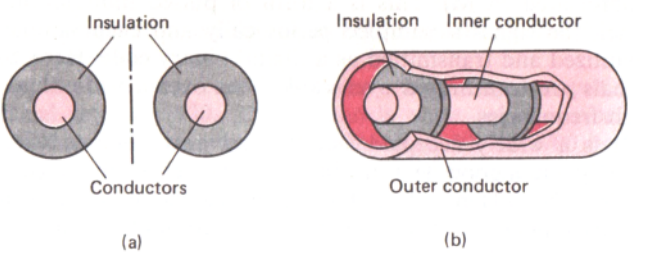


Fig. 7.9. Two-wire circuits: (*a*) balanced; (*b*) coaxial

plane. What we have then is called a balanced line or circuit. Quite aptly, cables made up of balanced pairs or quads are likewise called balanced.

If, on the other hand, the 'go' and 'return' conductors are not balanced in the sense defined above, we have an unbalanced line or circuit, and this happens in coaxial cables. The name 'coaxial' comes from the fact that one conductor completely surrounds the other, the two being coaxial, or concentric, and separated by a dielectric. Cables produced by stranding together coaxial pairs go by the name of coaxial cables. Sometimes, a cable may be a combination of both.

The reader may have noticed that the conductors of a balanced (twin or quad) cable have often been referred to as 'wires'. In a coaxial cable, however, this is only true of the central, or inner, conductor, while the job of a second wire is done by a tube or a braid, known as the outer conductor.

BALANCED CABLES

Present-day long-distance cables fall as a rule in the carrier-frequency class. Voice-frequency cables have retained a secondary role in short lines, such as branches from a major line.

Carrier-frequency balanced cables use copper conductors 1.2 or 1.3 millimetres in diameter; voice-frequency cables use wires smaller in diameter – 0.8 and 0.9 millimetre. It would be advantageous to use tubular or copper-clad aluminium conductors. The point is that they carry an alternating current which gives rise to an internal and an external alternating magnetic field, and these fields bring about eddy currents in the conductors. As a result, the high-frequency current tends to flow near the surface of the conductors. Thus, it is restricted to a small part of the total sectional area. This is known as skin effect. As the frequency of the current increases, the part where

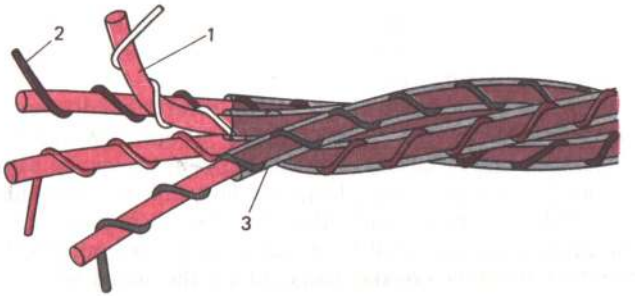


Fig. 7.10. Quad of copper conductors (*1*) insulated with polystyrene string (*2*) and polystyrene tape (*3*)

the current is now concentrated decreases in thickness. The skin depth is

$$\theta = 67f^{-1/2}$$

where f is the frequency in hertz, and the skin depth is in millimetres.

Since the h. f. current is concentrated within the outer skin layer, one could well use a tubular conductor or a clad conductor in which the outer layer of copper is applied over a less conductive and less expensive material, such as aluminium. Obviously, large quantities of copper could be saved theoretically. Unfortunately tubular or copper-clad conductors are more difficult to make, they are less robust, and their properties are less stable than those of all-copper conductors. All of these factors still stand in the way of using tubular and copper-clad conductors on a commercial scale.

Carrier-frequency cables use what is known as string insulation – the best class of insulation of all. It may be in the form of polystyrene strings, paper strings, or polyethylene strings. The key element is a string of an applicable material

over which is formed a lapping either by winding a helix of 0.05 millimetre polystyrene film or 0.12 millimetre cable paper, or by extruding a polyethylene cover over it. Since the string has a diameter which is about two-thirds of that of the conductor, it acts as a spacer and holds the lapping formed on top away from the surface of the conductor. As a result, a large percentage of the volume between the conductor and the insulation is air – the most efficient of all dielectrics.

String-insulated cables have the lowest equivalent permittivity and, in consequence, the lowest capacitance per unit length. While the effective capacitance of conventional city or local cables is forty-five to fifty-five nanofarads per kilometre, that of carrier-frequency cables is twenty-one to twenty-five nanofarads per kilometre, or half as large.

Carrier frequency cables may also use continuous and foamed (or expanded) polyethylene insulation, depending on their application and service conditions.

Importantly, carrier-frequency cables are manufactured to far more stringent tolerances than are specified for local or city cables. This point is illustrated in Table 10.

The groups of individual conductors in carrier-frequency cables are most often laid up into star quads, although some countries also use multiple-twin formation. As more ground is gained by digital transmission system using time division multiplexing (including primary systems operated at up to two megahertz, secondary systems operated at up to eight megahertz, tertiary systems operated at up to thirty-four megahertz and quaternary systems operated at up to one hundred and forty megahertz *), ever more interest is shown to multiple-twin construction since it safeguards against mutual interference

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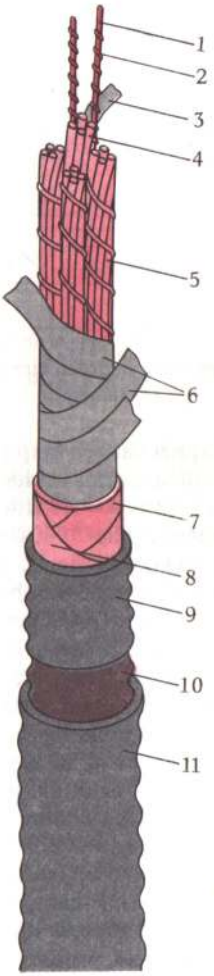
* The respective number of channels and speed of transmission (in kilobits per second) are: 30 and 2048, 120 and 8448, 480 and 34 368, 1920 and 139 264.

Table 10. Comparison between Carrier-Frequency Long-Distance Cables Using Polystyrene-String Insulation and Local Cables Using Continuous Polyethylene Insulation

Particulars	Ratings	
	polystyrene-string insulation	continuous polyethylene insulation
Conductors:		
diameter, mm	1.2	0.5
tolerance on diameter, mm	±0.005	±0.01
same as %	±0.4	±2
Insulation:		
thickness, mm	0.845	0.25
tolerance on thickness, mm	±0.035	±0.05
same as %	±4.15	±20
Insulated conductors:		
diameter, mm	2.89	1.0
tolerance on diameter, mm	±0.04	±0.11
same as %	±2.1	±11

best of all. Carrier-frequency cables use small numbers of quads – from three to twelve, mostly four and seven. Voice-frequency long-distance cables may use as many as one hundred or even two hundred quads. Some countries are still using coil-loaded cables and phantom circuits, in which cases the cable core is laid up in concentric layer formation.

Fig. 7.11. Seven-quad, balanced, carrier-frequency intercity cable using polystyrene-string insulation: *1*, copper conductor 1.2 mm in dia.; *2*, polystyrene string whipping; *3*, polystyrene film lapping; *4*, insulated conductors; *5*, twisted quad; *6*, paper belt insulation; *7*, aluminium shield; *8*, synthetic-film barrier; *9*, corrugated steel sheath; *10*, anti-corrosion asphalt covering; *11*, polyethylene jacket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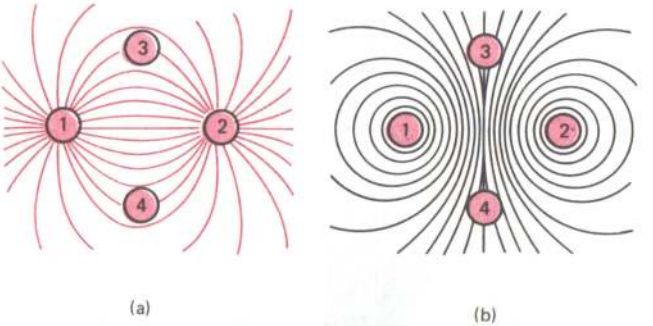

Fig. 7.12. Mutual interference between circuits in a cable: (*a*) electric; (*b*) magnetic

In 1936, twelve-channel carrier-frequency systems went into operation, using unloaded carrier cables. The total range of the twelve basebands was $12 \times 4 = 48$ kilohertz, extending from twelve to sixty kilohertz. The 1940s saw the emergence of 24-channel carrier-frequency systems, with a total frequency range extending from 12 to 108 kilohertz. At present, use is made of 60-channel carrier-frequency systems (12 to 252 kilohertz) and 120-channel carrier-frequency systems (12 to 552 kilohertz), operating by frequency division multiplexing. There are also systems with fewer channels, notably between zone and group telephone exchanges.

The range of frequencies that can be transmitted over balanced circuits is limited by mutual interference. The current flowing in circuit I formed by conductors *1* and *2* of a quad sets up around them an alternating electric field which threads conductors *3* and *4* that make up circuit II, so that a potential difference is produced between them. There is also a magnetic field set up around the conductors in a similar way, with the result that the magnetic field produced around conductors *1*

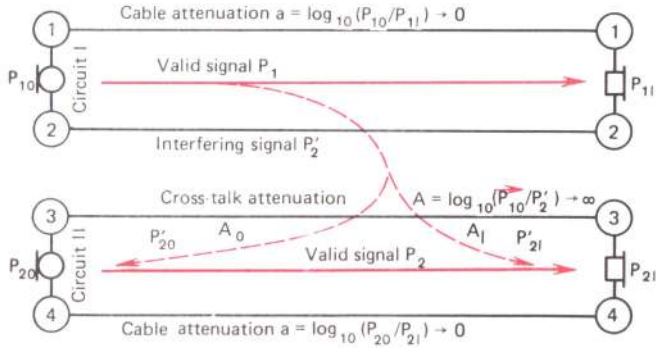

Fig. 7.13. Valid signal, P, and interference, P', in cable circuits

and *2* gives rise to an electromotive force in conductors *3* and *4*. Because of this, the 'useful' current in circuit II is accompanied by an interfering current: the parties at the sending and receiving ends can hardly carry on their conversation because of noise and scraps and bits of conversations from other circuits. That is why this form of interference is called cross-talk.

Naturally, efforts are usually made to reduce cross-talk power as much as practicable. Suppose the useful signal transmitted over circuit I has a power P_1. The interfering signal coupled into circuit II carries with it a power P'_2 which reaches the telephone receivers at both the sending and the receiving ends of the telephone line (the respective powers are labelled as P'_{20} and P'_{2l} in Figure 7.13. Of course, it is desirable that the interfering signal should be as small a fraction of the valid signal as possible. As has been noted earlier, every circuit introduces what we've called 'natural attenuation', symbolized as a. It has also been explained that for a transmitted signal to be properly understood, at least one-thousandth of the original

signal power should reach the receiver. This implies that the natural attenuation should be not over thirty decibels.

How well circuits are protected against mutual interference is stated in terms of cross-talk attenuation A. In contrast to natural attenuation, every effort is made to keep cross-talk attenuation as high as can be achieved, so that adjacent circuits in a cable could reliably be protected against mutual interference. Cross-talk attenuation is defined as the ratio of the useful signal power to the cross-talk power:

$$A = 10 \log_{10}(P_1/P_2)$$

The quality of transmission is taken to be satisfactory if the cross-talk power is one-millionth to one ten-millionth of the useful signal power. That is, the cross-talk attenuation must at least be equal to

$$A = 10 \log_{10}(10^6\text{-}10^7) = 60 \text{ to } 70 \text{ decibels}$$

at the highest signal frequency.

We would have an ideal circuit if it always showed a 'green' light to the valid signal and attenuated it very little, if at all, and a 'red' light to the cross-talk and attenuated it completely. Unfortunately, some degree of cross-talk between balanced circuits is practically inevitable and as inevitably it increases (which means a decrease in cross-talk attenuation) with rising frequency.

COAXIAL CABLES

It is fashionable to value events on a 'century' scale. The assassination of John Kennedy, the 35th President of the United States, in 1963 went down into history as the Crime of the Century. The theft of money from a mail train in Britain was presented by the mass media as the Robbery of the Century. Sports newspapers have struck the tag of the Jump of the Century to what Bob Bimon did at the 1968 Olympic Games in Mexico.

What about discoveries and inventions? How can one go about assessing the absolute significance of what is done in different fields of science and technology? Would it be legitimate to place the discovery of superconduction above the invention of the laser, the splitting of the atomic nucleus, or advances in gene engineering? In this author's opinion, it is more appropriate to make comparisons within a particular field of engineering or even within narrower limits.

With regard to cable technology, several candidates have been named to receive the title of the Invention of the Century, among them the Glover barrier, the SZ-laid-up cable, and the deep-water cable using a support rope enclosed inside instead of an armour (to be described later). The author gives his preferences to the coaxial cable – this phenomenal feat of twentieth-century cable technology.

The idea of using a coaxial cable for carrier-frequency multichannel transmission was first advanced by S. Schelkunov, a Bell System engineer. He published his theory of coaxial cables for communication in 1934. The unique property of coaxial cables as compared with balanced cables is the fact that the protection they give against mutual interference improves, rather than degrades, with rising frequency.

The electric field in a coaxial cable is confined between the inner, or centre, conductor and the outer conductor, so that no electric field exists outside the cable. Nor is there any magnetic field. At any point in space outside a coaxial pair, the strength of the magnetic field set up by each of the straight conductors is given by

$$H = I/2\pi r$$

where

I = current flowing in the conductor

r = distance from the point in question to the centre of the conductor which may be solid or tubular

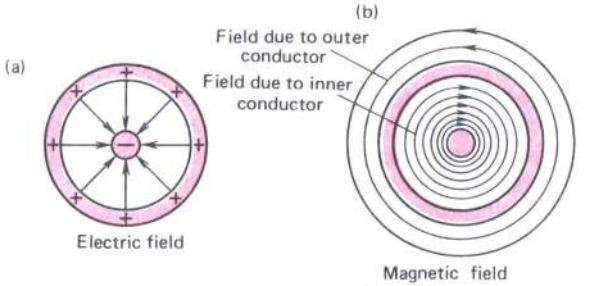

Fig. 7.14. Fields set up by a coaxial pair: (*a*) electric field; (*b*) magnetic field

Since the same current is flowing in the two conductors but in opposite directions, and the centre of the conductors in a coaxial pair is common to both, we have

$$H_{inner} = I/2\pi r$$
$$H_{outer} = -I/2\pi r$$

and

$$H_{result} = H_{inner} + H_{outer} = 0$$

Thus, a coaxial pair does not set up an appreciable external electromagnetic field and cannot therefore interfere markedly with adjacent coaxial pairs. In this, a coaxial pair (or 'tube', as it is called technically) compares favourably with a balanced pair which produces a fairly large electromagnetic field reaching out to a sizeable distance.

Because of skin effect, high-frequency currents tend to flow in a coaxial cable on the inside surface of the outer conductor and on the outside surface of the inner conductor. As the frequency rises, the current is crowded more and more to the respective surfaces, and the skin depth is decreased. Since real coaxial lines are never ideal, they give rise to spurious

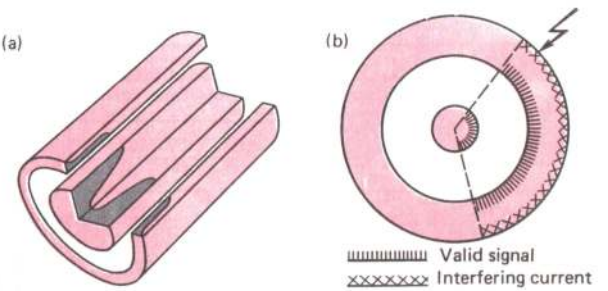

Fig. 7.15. Current distribution in a coaxial pair: (*a*) signal currents; (*b*) sum of signal and noise current in the outer conductor (shield)

high-frequency electromagnetic fields, and these inevitably couple with adjacent coaxial lines. The same goes for the fields set up by external sources, such as radio transmitters. In either case however, the field is confined to the outer surface of the line rather than over its entire cross-section.

Thus, the outer conductor of a coaxial 'tube' doubles as the 'return' conductor of the circuit and as a shield screening the valid signal against corruption by noise and interference.

Owing to their better noise immunity with rising frequency, coaxial cables can each carry tens or even hundreds of times more telephone conversations than balanced cables. This is the reason why coaxial cables predominate on major long-distance telephone lines in all countries.

The first coaxial cable (see Table 11) was installed in 1936 on a pilot line between New York and Philadelphia. It had two coaxial tubes which could carry 224 two-way telephone conversations over a total frequency range of one megahertz. The progress in the use of coaxial lines in the ensuing years in the USA is illustrated in Table 11.

The numerals describing the type of cable stand as follows: the first figure gives the number of coaxial pairs or tubes, the

Table 11. Coaxial Lines in the United States

Year	Cable type	Max. frequency, MHz	Number of telephone conversations carried		Repeater spacing, km
			by one tube	by entire cable	
1936	2 × 1.83/6.7	1	224	224	16
1941	4 × 1.83/6.7	3	600	1200	8
1947	8 × 2.6/9.5	3	600	1800	12.8
1953	8 × 2.6/9.5	8	1860	5580	6.4
1962	12 × 2.6/9.5	8	1860	9300	6.4
1965	20 × 2.6/9.5	8	1860	16 740	6.4
1967	20 × 2.6/9.5	17.5	3600	32 400	3.2
1974	22 × 2.6/9.5	60	10 800	108 000	1.6

second (the numerator) gives the diameter of the inner conductor, and the third (the denominator) gives the inside diameter of the outer conductor. All dimensions are given in millimetres.

From a look at the table the reader will, I'm sure, say: "The sums don't tally!" And he will be right because if one coaxial tube can carry six hundred telephone conversations, why is it that a cable made up of eight coaxial tubes has a capacity which is only three, and not eight, times as great? For one thing, all 2.6/9.5 cables have each two tubes as spares. For another, and more importantly, the difference arises from the way in which carrier-frequency telephone transmission is organized. In conventional telephone systems, the conversation from subscriber *A* to subscriber *B* and back is transmitted over the same physical two-wire circuit. In carrier telephony over either balanced or coaxial lines, any one of two schemes may be used: four-wire and two-wire.

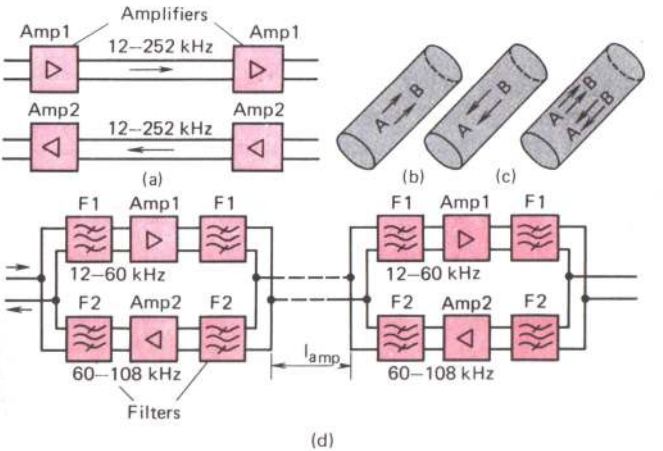

Fig. 7.16. Carrier communication systems: (*a*) four-wire; (*b*) four-wire two-cable; (*c*) four-wire single-cable; (*d*) two-wire

With a physically four-wire scheme, each telephone conversation is allotted two pairs in a cable: one for transmission from subscriber *A* to subscriber *B* (Figure 7.16*a*), and the other in the reverse direction, with the same frequency range, say, from 12 to 252 kilohertz, used in both directions. Therefore when we say that each pair carries, for example, sixty channels, our statement is inaccurate because two pairs and not one are needed to accommodate sixty channels.

To calculate the overall capacity, N, of a cable, first divide its number of pairs p by two, and multiply the result by the number n of channels in the system:

$$N = (p/2)\,n$$

For example, when a balanced $4 \times 4 \times 1.2$ cable is used for sixty-channel operation in 12-252-kilohertz bandwidth

($n = 240:4 = 60$), it will carry a total of

$$N = (8/2) \times 60 = 240$$

telephone conversations.

To reduce mutual interference between the circuits of balanced cables, it is sometimes practised to install two cables in the same trench. Then all pairs in one cable are used for transmission from *A* to *B*, and all pairs in the other for transmission from *B* to *A* (Figure 7.16*b*). The situation is different with coaxial cables. Since coaxial tubes are highly immune to noise and cross-talk, it is usual to encase all tubes in one sheath to make a single cable (Figure 7.16*c*). Then, in a twelve-tube coaxial cable, on subtracting the two spare ones, we will have ten tubes in use. When used in a 1860-channel system, it can carry as many as $5 \times 1860 = 9300$ telephone conversations.

The two-wire scheme (Figure 7.16*d*) differs in that a conversation proceeds over the same physical circuit in both directions, but in different frequency bands which may extend from twelve to sixty kilohertz for transmission from *A* to *B*, and between sixty and one hundred and eight kilohertz for transmission from *B* to *A*. In order to separate the two frequency bands from each other, suitable filters are installed at the input and output of each repeater. Given the same total frequency range, the overall capacity of the cable in the case of a two-wire scheme will be the same as with a physically four-wire scheme. Taking the previous example again, as few as thirty, and not sixty, channels can be carried in each direction:

$$n = 120 \text{ kHz} \div 4 \text{ kHz} = 30 \text{ channels}$$

Therefore, the total number of channels handled by a $4 \times 4 \times 1.2$ cable will be

$$N = pn = 8 \times 30 = 240$$

Fig. 7.17. Powered laying of long-distance cables

Coaxial cables are unique in both properties and applications. They are the only choice for TV service because the transmission of telecasts calls for a bandwidth of six megahertz. In a multitube coaxial cable, some tubes are ordinarily used to transmit TV programs (likewise two tubes for both directions), and some for multichannel telephony.

Before we pass on to the construction of coaxial cables, a few remarks are in order about their history.

In a book on coaxial lines, published in the USSR in the early 1950s, it is said that their theory was formulated by P. Voinarovsky in 1912, but their commercial production didn't begin until 1930 – the time when radio-frequency polymer dielectrics first appeared. The same statement can be found in some other books. I find it hard to agree with them. Let's see why.

P. Voinarovsky (1866-1913), an outstanding Russian electrician and telecommunication specialist, Professor at and Rector of the Electrotechnical Institute in St. Petersburg, wrote his 200-page book, "A Theory of Electric Cables", in 1912. A bibliographic rarity today, it was well turned out and has therefore been well preserved even now. It was a substantial treatise on cable technology, the first in Russia and among the first in the world. Voinarovsky examined two- and three-conductor cables, both balanced and coaxial. In fact, he used another term, 'concentric', and what he named 'a three-conductor concentric cable' is now called simply 'triaxial'. But the crucial point is that they were power cables – those intended for power transmission. In this connection it seems relevant to quote F. Engels: "... in every field of science, in natural as in historical science, one must proceed from the given *facts*..., ... the interconnections are not to be built into the facts but to be discovered in them, and when discovered to be verified as far as possible by experiment."* The power cables were common at the turn of the century, but abandoned later. This fact was stressed by V. Lebedev, a prominent Soviet authority on cable technology, in his substantial work, "Power Cables", which was published in 1936.

Indeed, it never occurred to Voinarovsky that concentric cables could ever be used in communications. He found that a concentric (coaxial) pair produced no external magnetic field, and calculated its internal field at a power frequency of 50 hertz. He wrote nothing about the propagation of high-frequency current over the cross-section of the conductors that make up a coaxial pair or about the shielding effect of the outer conductor – he hadn't explored the matters at all. Almost all of his book has to do with power cables, and only a small

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* Engels F. *Dialectics of Nature*. Old Preface to [Anti]-Dühring on Dialectics.

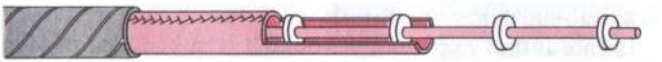


Fig. 7.18. Coaxial pair using polyethylene disc insulation and a 'zipper' seam on the outer conductor

section at the end of Chapter 2 deals with a very general theory of line communication.

In the first decade of this century there was nothing yet to stimulate a quest for a theory of r.f. coaxial cables. The need for a theory arose with advances in multichannel transmission systems in the third decade. The earliest coaxial cables with an even number of pairs were commercially manufactured in 1935 and not in 1930, after a basic theory had been formulated.

Until about the mid-1960s, the basic type of coaxial pair standardized throughout the world in compliance with recommendations of the International Telegraph and Telephone Consultative Committee (usually known by its French abbreviation as the CCITT) was the 2.6/9.5 pair. As telecommunications moved higher up the frequency scale and the handling capacity of the pair increased, a decision was taken to make a smaller coaxial pair that would carry fewer channels but would be more economical. That is how a 1.2/4.4 pair has been standardized.

National standards permit slight variations in the standard dimensions. For example, 2.6/9.4 and 2.65/9.5, or 1.2/4.6. In contrast to the 2.6/9.5 pair, the 1.2/4.4 pair was named 'small-sized', but no special name was coined for the 2.6/9.5 pair. At first, it was called 'standard' or 'normal'. After the 1.2/4.4 pair had also been standardized, however, the term 'standard' became obviously misleading, and the name 'normal' would suggest that all the other pairs were 'abnormal' somehow. Later other pair sizes were developed, such as

0.7/2.9, 0.9/3.2, 3.7/13.5, 4.1/15, 5/18, 6.85/24.75, and 7/27. What about names for them?

In this author's opinion, it wouldn't be a bad idea to follow the suit of women's fashion as a more flexible one. Indeed, the words 'mini', 'midi' and 'maxi' are terse and suggestive. Then we would have microcoaxial cables with a central conductor up to one millimetre in diameter, minicoaxial cables with a central conductor from 1.01 to 2 millimetres in diameter, midicoaxial cables with a central conductor from 2.01 to 3 millimetres in diameter, and maxicoaxial cables with a central conductor more than three millimetres in diameter.

The inner conductor of a coaxial cable is a solid copper wire. It is not at all unlikely that copper-clad aluminium conductors may be used some time in the future, with a copper cladding 0.03 to 0.2 millimetre thick, depending on the wire diameter.

It is an extremely formidable manufacturing task to shape an ideal outer conductor as a smooth, seamless tube. Instead, a copper tape 0.15 to 0.3 millimetre thick is formed into a tube which has only one longitudinal seam. At one time, the tape was stamped so as to produce a 'zipper' seam; today the usual practice is to make fine corrugations at the edges.

The outer conductor is one and a half to two times as heavy as the inner conductor, but its resistance is smaller in the same proportion. Therefore, it is economically more attractive to use aluminium instead of copper for the outer conductor. Such a coaxial cable has an attenuation which is only slightly – a mere six per cent – greater than that of its copper counterpart. In fact, this increase in attenuation may be avoided by increasing the size of the pair from, say, 2.6/9.5 to 2.8/10.2.

The insulation types used by coaxial cables are many and varied. Most often, the insulation is in the form of polyethylene discs of thickness $\delta = 1.8 \pm 0.1$ millimetres, spaced a distance $h = 30$ millimetres apart. This type of insulation has the lowest equivalent relative permittivity which depends on the relative

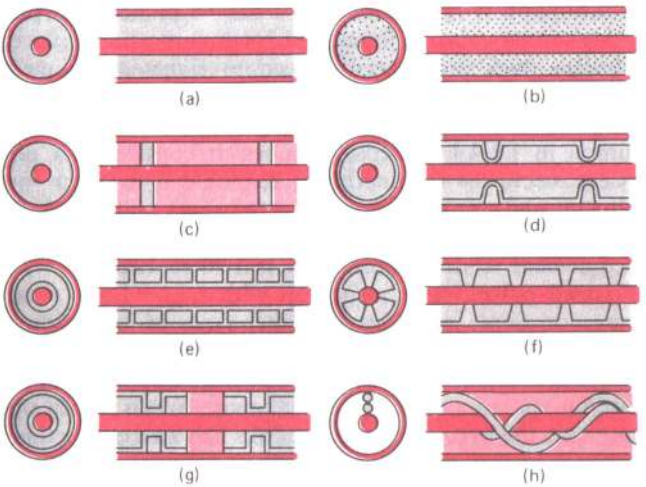


Fig. 7.19. Insulation for coaxial pairs: (*a*) solid polyethylene; (*b*) expanded polyethylene; (*c*) disc; (*d*) balloon; (*e*) bamboo; (*f*) tape-frame; (*g*) bead; (*h*) polystyrene string

volumes occupied by air and polyethylene and is given by a simple equation

$$\varepsilon_{r,eq} = 1 + \delta/h \times 1.3$$

On substituting for δ and h, we get: $\varepsilon_{r,eq} = 1.08$.

Polyethylene spacing discs can be either forced onto the inner conductor (in which case, they should have a radial slit), or moulded on the conductor directly. Moulding is preferable because polyethylene discs without a radial slit are more robust. Discs may be moulded intermittently on four to six wires or continuously on one wire. As a way of reducing the volume of solid polyethylene, discs are sometimes shaped as beads or have hollows on one, two or four sides. Polyethylene

disc insulation is most common in 2.6/9.5 midicoaxial pairs, although it may also be found in 1.2/4.4 pairs where discs one millimetre thick are spaced sixteen to eighteen millimetres apart.

Another form of insulation is the balloon type, most common in 1.2/4.4 minicoaxial tubes. It consists of a polyethylene sleeve 0.4 millimetre thick, moulded over the inner conductor and crimped every fifteen to twenty millimetres. The resultant continuous insulation appears as a string of balloons. Its equivalent relative permittivity is 1.20 to 1.25.

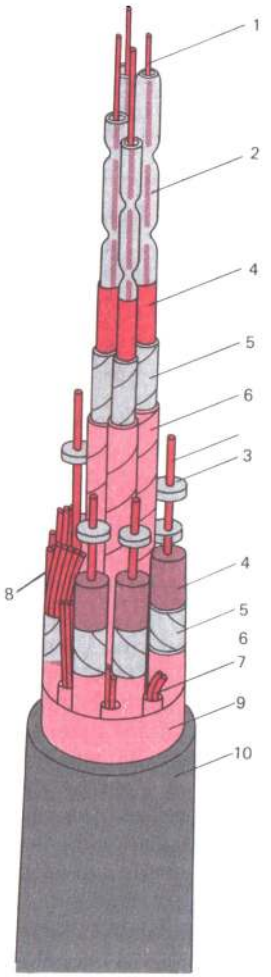
Foamed polyethylene insulation with $\varepsilon_{r,eq} = 1.5$ is a rarer occurrence. Some countries use other types of insulation.

What is called bamboo insulation, used in 1.2/4.4 coaxial tubes, is a thin-walled polyethylene tubing made integral with partitions spaced a regular distance apart. When ripped open lengthwise, this type of insulation looks like an axial section of bamboo.

Bead insulation uses polyethylene beads twelve millimetres long strung on the inner conductor 1.2 millimetres in diameter at a pitch of six millimetres. String insulation may use one or two polystyrene strings which act as spacers and hold the outer covering away from the surface of the conductor, thus increasing the volume taken up by air. The outer covering may be solid polyethylene or polystyrene tape.

Cable makers in Japan have developed a type of insulation which uses polyethylene tape 0.4 millimetre thick. On one side,

Fig. 7.20. Intercity composite coaxial cable consisting of four 1.2/4.4 coaxials (or 'tubes') with air-space polyethylene-balloon insulation and six 2.6/9.5 coaxials with air-space polyethylene-disc insulation: *1*, inner single-wire copper conductors; *2*, balloon insulation; *3*, disc insulation; *4*, outer tubular copper conductor; *5*, steel-tape shield; *6*, paper-tape wrapping; *7*, service pairs; *8*, balanced quads; *9*, core wrapping (belt insulation); *10*, lead sheath


1
2
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10

Table 12. Multichannel FDM Telephony Systems Using Coaxial Cables

Number of telephone channels (over two pairs)	Frequency bandwidth, MHz	Repeater hop, km
	2.6/9.5 coaxials	
900-960	4	9
1200-1260	6	8
1800-1920	8.5	6
2700	12	4.5
3600	18	3
10 800	60	1.5
	1.2/4.4 coaxials	
300	1.3	6-8
900-1020	4.0-4.5	4
1200-1260	6	3
2700	12	2
3600	18	1.5

the tape has groups of four ribs 1.2 millimetres high, spaced twelve millimetres apart. The tape is placed around the inner conductor longitudinally, and its ribs hold the conductor accurately centred, while the ribs themselves are at right angles to one another. That is what may be called tape-frame insulation.

For the most part, present-day coaxial cables encase in one metal sheath several coaxial 'tubes', or simply 'coaxials' differing in size, balanced quads and pairs, and even individual insulated conductors. An apt example is the Soviet-made type KM-8/6 composite long-distance cable. It encases in one sheath eight 2.6/9.4 coaxials, six 1.2/4.6 coaxials, one quad,

Table 13. Comparison of Balanced and Coaxial Lines

Line element	Weight of copper, kg/km	Number of channels	Weight of copper per channel per km, kg
One balanced quad (1 × 4 × 1.2)	40.3	12	3.36
		24	1.68
		60*	0.67
		120	0.34
Two coaxials (2 × 1.2/4.6)	62.8	300	0.21
		1020	0.06
Two coaxials (2 × 2.6/9.5)	241.4	1920	0.126
		3600	0.067
		10 800	0.022

* A scheme has been developed and being commercialized (at this writing) in the Soviet Union for a 4 × 4 × 1.2 balanced cable. Three quads of the four are to be used for 60-channel carrier telephony, and one quad for 1020-channel carrier telephony. As a result, a two-cable line can handle nearly three times as many telephone calls and the weight of copper per channel per kilometre is reduced to less than a quarter of a kilogram.

eight twins, and six individual conductors. The 2.6/9.4 coaxials can be used for long-distance multichannel operation, and the 1.2/4.6 coaxials for communication between intermediate points along a route for which a smaller number of channels may be needed. Some of the balanced circuits are used for carrier telephony (over, say, as many as twenty-four channels) between small communities, and some for supervisory and maintenance purposes. The individual conductors are used for telemetry and telecontrol. All in all, the KM-8/6 composite cable can provide a total of 10 800 channels over the 2.6/9.5

coaxials and 1020 channels over the 1.2/4.6 coaxials so that a total of 46 260 telephone conversations can be transmitted at a time (provided no coaxials are held as spares).

Of course, there may be other combinations of coaxials, balanced circuits and individual conductors encased in a single cable sheath, and they may be used for other types of multichannel operation.

Coaxial lines are more economical than their balanced equivalents. This can clearly be seen from Table 13 where they are compared in terms of the copper required to build one kilometre of line and to carry one telephone channel (or conversation).

Is the sixty-megahertz bandwidth a limit for coaxial cable? The answer is "No". In the 1970s, work was started on carrier telephone systems intended to span a frequency range of two hundred megahertz and six hundred megahertz and to provide thirty thousand and ninety thousand channels, respectively. The coaxial cables for such systems would have to have an inner conductor ten to twelve millimetres in diameter and an outer conductor forty to forty-five millimetres in diameter. With existing sizes of coaxial cables, the repeater hop would have been drastically reduced, and repeaters would have to be installed a few hundred metres apart.

In recent years, the pace of work on these projects has slowed down, however, and emphasis in long-distance communications has been shifted to optical fibre cables.

Chapter Eight
Across the Seas and Oceans

UNDERWATER TELEPHONE CABLES

We parted with underwater cables at the turn of the century when telegraph cables using gutta-percha insulation had reached the peak in their enchanting rise.

Of course, it would be an oversimplification to think that there can be a well-defined, tangible division line between successive periods in history: here is the end of one and the start of the next. No, underwater (including transoceanic) telegraph cables were still being installed throughout the first third of the twentieth century, but the limelight had been stolen by telephone cables.

In contrast to the nineteenth century when underwater telegraph cables suddenly passed ahead of underground cables, underwater telephone cables have, in the twentieth century, been developing in parallel with their underground counterparts. With no delay at all, inductive (coil and continuous) loading was applied to underwater cables in order to enhance transmission distances. Gutta-percha insulation gradually gave way to air-space insulation which had half as great electric capacitance. Protection against ingress of water was provided by a lead sheath supported by a helix of steel tape or suitably shaped steel wire. Cables of this construction could be installed at depths down to one kilometre. Guttapercha-insulated cables consisted of only one quad, while air-space insulated cables could have from one quad (or pair) to twelve.

However, neither inductive loading nor the use (since the 1920s) of tube amplifiers could help transoceanic telephone lines to make a decisive jump up the el-scale. The transmission distance over underwater telephone cables in the first half of

Table 14. Underwater Voice-Frequency Telephone Lines Used in the Early Twentieth Century

Line	Year of construction	Length, km	Insulation	Conductor assembly	Type of loading	Attenuation *, dB/km
Sweden-Denmark	1902	5.3	G	1 × 4 × 2.1	Cont.**	0.17
Germany-Denmark	1903	19.3	A-S	1 × 4 × 3.6	Cont.	0.10
Germany-Helgoland	1903	80.6	A-S	1 × 2 × 4.0	Cont.	0.06
Jutland (Denmark)-Zealand	1904	40	G	1 × 4 × 3.3	Cont.	0.10
Germany-Switzerland	1906	12.6	A-S	7 × 2 × 1.5	Coil	0.09
England-France	1910	43.4	G	1 × 4 × 2.4	Coil	0.10
England-Belgium	1911	90	G	1 × 4 × 2.4	Coil	0.09
England-Ireland	1913	118	G	1 × 4 × 2.4	Coil	0.07
Germany-Sweden	1919	120.5	A-S	1 × 4 × 2.1	Cont.	0.13
England-Netherlands	1922	152.6	G	1 × 4 × 2.4	Coil	0.07
Germany-Eastern Prussia	1922	175.5	A-S	3 × 4 × 1.9	Cont.	0.12
England-Netherlands	1924	159	A-S	4 × 4 × 2.35	Cont.	0.09
Germany-Denmark	1926	45.8	A-S	12 × 4 × 1.0	Coil	0.30
Germany-Sweden	1927	118	A-S	12 × 4 × 1.5	Coil	0.16

* At 800 hertz.
** One, two or three layers of iron wire 0.2 or 0.3 millimetre in diameter.

Note: G, gutta-percha insulation; A-S, air-space insulation; Cont., continuous loading; Coil, coil loading.

the twentieth century didn't exceed two hundred kilometres. It is often asked: Why is it that telegraph cables could cross the oceans and telephone cables couldn't? The answer is simple: Everything pivots on the frequencies used for transmission. Telegraphy uses frequencies from a few hertz to tens of hertz, and the frequencies used for telephony early in the twentieth century ranged from 300 to 2700 hertz.

As will be recalled, the cable attenuation α increases with rising frequency, f or ω, with the result that the transmission distance decreases:

$$l = a/\alpha$$

Only terminal amplifiers were installed at the shore ends of a line. While land lines using underground cables could be equipped with intermediate repeaters spaced a few tens of kilometres apart, this opportunity was nonexistent for underwater lines. It was a long time before ways and means were devised to build reliable and durable repeaters for underwater service, and durable they must be because the pressure of water goes one atmosphere up with an increase of ten metres in depth.

The world's first underwater coaxial cable was laid between Key West, Florida and Havana, Cuba in 1921. That was a continuosly loaded, guttapercha-insulated, voice-frequency cable for telephony and telegraphy. Its total frequency range of 3800 hertz could be used to derive four telegraph channels and one telephone channel. In fact, three cables were installed along the route 190 kilometres long. In contrast to single-conductor telegraph cables in which the 'return' path was provided by seawater and, partly, by the armour, these cables had an outer conductor wound as a helix of two copper tapes. This markedly brought down the resistance of the return path – a factor of special importance to telephony.

As an aside, it may be noted that this is an example in which

coaxial construction was not a mandatory feature in order to provide carrier-frequency operation.

However, underwater cables (also called 'submarine' where applicable) were moving up the ef-scale much faster than up the el-scale. The world's first carrier-frequency submarine coaxial cables were installed in 1929 along a 37-kilometre route from Spain across the Strait of Gibraltar to Morocco and along a 75-kilometre route between Tenerife and Gran Canaria, two of Canary Islands. They were still guttapercha-insulated 3.9/12.6 cables with an outer conductor in the form of thirty-four copper wires each 0.9 millimetre in diameter, laid up in a single layer.

In 1930-1931, a 202-kilometre long cable was laid between Key West and Havana. It used a new insulating material, called paragutta, for the first time in cable technology. Paragutta, a mixture of gutta-percha, rubber and wax, markedly outperformed gutta-percha in electrical properties. As measured at a frequency of two kilohertz, the relative permittivity is 3.5 for gutta-percha and the loss tangent is 3×10^{-3} for the former, and $\frac{1}{7} \times 10^{-4}$ for the latter. This means the loss of energy in paragutta insulation is one-fortieth of what it is in gutta-percha. The 4.25/16.1 cable was designed to transmit three telephone conversations over a physically two-wire circuit in the frequency range 6.3-16.4 kilohertz in one direction and in the frequency range 18.4-28.5 kilohertz in the opposite direction.

In 1937, a 150-kilometre long line was laid between Aldbrough, England and Domburg, the Netherlands. It used two coaxial cables laid side by side. Each cable carried sixteen telephone channels with a total frequency range of sixty kilohertz in one direction. Thus, this was a physically four-wire, two-cable communication system.

In 1940, an experimental coaxial cable was laid in Britain. It had continuous polyethylene insulation. Before long, polyeth-

ylene came to be the principal insulating material for underwater cables.

It ought not to be thought that beginning in 1930 underwater telephone cables were solely of coaxial construction. Balanced cables for multichannel carrier telephony were also installed. The first of them, designed for use in shallow waters and continuously loaded, was installed in 1930 between Germany and Sweden on a line 120 kilometres long for two-channel transmission in the frequency range 0.3-5.2 kilohertz. It had a total of 42 quads made up of conductors 1.2 millimetres in diameter and a screened radio-frequency pair made of wire 1.75 millimetres in diameter (in short-hand, this description is written as $42 \times 4 \times 1.2 + 1 \times 2\text{scr} \times 1.75$). The quads were divided into two groups of twenty-one each, one group for transmission in one direction and the other in the opposite direction. The groups were separated by a metallized paper shield and formed a physically four-wire single-cable system. The cable used dry-core insulation and was encased in a lead sheath. It could carry eighty-four telephone conversations at a time.

A similar cable was installed on a 45-kilometre line between Dover, England and Calais, France in 1939, but it was designed for twelve-channel operation in the frequency range 12-60 kilohertz. Its central group of $7 \times 4 \times 1.3$ quads was separated from the $16 \times 2 \times 1.3$ pairs wound on top by an electromagnetic shield made up of alternating layers of copper and steel tape.

The problem of transoceanic telephony was solved with the advent of submarine, or submersible, repeaters in the 1940s.

The need for repeaters in a transoceanic line can be backed up by simple mathematics. The signal sent by a telephone transmitter into a line has a power of one milliwatt. Obviously, it is too small for the signal to cross the ocean and be received

there. It is as obvious that the signal must be boosted in power artificially, but by how much?

At this writing, the electric power plants in the Soviet Union generate between them a total of over three hundred gigawatts (the prefix 'giga' stands for 'million'). What will happen if we send all of this power over a transoceanic line? The sensitivity of a telephone receiver (that is, the smallest signal it can distinctly receive) is one microwatt. Therefore the line attenuation may be allowed to be as high as

$$\begin{aligned} a &= \log_{10}(P_0/P_l) \\ &= \log_{10}(3 \times 10^{11}/10^{-6}) \\ &= \log_{10}(3 \times 10^{17}) \\ &= 17.477 \text{ bells} = \text{approx. } 17.48 \text{ bells} \end{aligned}$$

As is seen from Table 14, the lowest attenuation at 800 hertz is displayed by a voice-frequency balanced cable using conductors four millimetres in diameter. The maximum transmission distance of such a cable would be

$$l = a/\alpha = 17.48/(6 \times 10^{-3}) = 2915 \text{ kilometres}$$

It follows then that even the gigantic power of three hundred gigawatts would not be enough to transmit one telephone conversation from the European coast of the Atlantic to Newfoundland.

In our hypothetical example, the transmitted power is reduced to one-tenth ($a_1 = 1$ bell, $P_{l1} = 0.1P_0$) as the signal travels a distance $l_1 = a/\alpha = 1/0.006 = 167$ kilometres.

This is not to mean, as is sometimes erroneously thought, that on travelling a distance of 1670 kilometres the input power P_l will have been reduced merely by a factor of a hundred. The point is that it changes with the distance travelled in a different manner: as l_1 increases ten-fold (so that $l_2 = 1670$ kilometres), the attenuation $a_2 = \alpha l_2$ rises to 10 bells. Therefore, P_{l2} will have been reduced not by a factor of a

hundred, but by a factor of ten thousand million; that is, it will have diminished to one-ten thousand millionth of the previous figure. Now it is clear why intermediate repeaters are a 'must' on transoceanic cables.

The first submarine repeater was installed in 1943 on an experimental cable laid by the British Post Office between Anglesey and the Isle of Man in the Irish Sea. As Arthur Clarke describes it, the device was encased in a stubby rigid tube "about the size and shape of torpedo, and the cable ship has to be brought to a full stop when it is time to lay one". The coaxial cable 82 kilometres long could carry forty-eight channels in the frequency bands 16 to 208 kilohertz and 312 to 504 kilohertz. In 1946, a submarine repeater was built into the cable laid between Lowestoft, England, and the Borkum Island, Western Germany in the North Sea, spanning a distance of 366 kilometres. Thus, it exceeded the 200-kilometre limit that had existed for submarine long-distance cables. The cable operated at frequencies up to 43.4 kilohertz; the repeater remained in service for eighteen years and was not removed from service until 1964.

Special mention should be made of the cable installed in 1947 on the Aldbrough, England – Domburg, the Netherlands line 152 kilometres long. It was a 3.25/12/43.2 triaxial cable which had two coaxial tubes: a central 3.25/12 pair and a 12/43.2 outer pair. The central pair used solid polyethylene insulation, and the outer pair, polyethylene-string insulation. The intermediate conductor (external to the central tube and internal to the outer tube) was made up of several copper tapes. The helix of polyethylene string 5.6 millimetres in diameter was wound over the intermediate conductor with a pitch of twenty-five millimetres. Extruded over the polyethylene string was a polyethylene tube whose outside diameter was 43.2 millimetres. The outer conductor was made up of six copper tapes. The cable armour was of the usual

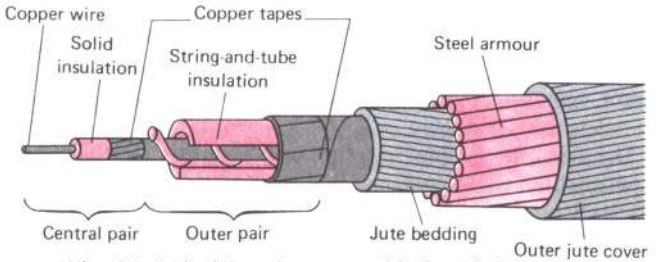


Fig. 8.1. Triaxial underwater cable installed in 1947

construction. The outer tube could carry eighty-four telephone conversations in the frequency bands 24 to 372 kilohertz and 456 to 804 kilohertz.

The years 1950 and 1956 saw the installation of quite a number of predominantly submarine telephone cable lines, each using from one to seven vacuum-tube repeaters. The longest of them was the 566-kilometre line laid between Aberdeen, Scotland and Bergen, Norway in 1954. During those years, the range of frequencies used for telephone transmission expanded from 12-108 to 60-1164 kilohertz, and the number of channels rose from 24 to 120. The lines were mainly two-wire single-cable systems using different frequency bands for the 'east-west' and 'west-east' circuits, for example 24-168 and 208-352 or 24-264 and 312-552 kilohertz. All of those cables, complete with two-way repeaters enclosed in tubular steel capsules, were installed at depths not over five hundred metres.

At the same time work was under way on ways and means of laying cables and repeaters non-stop at oceanic depths. It was proposed to use one-way repeaters built each into a series of flexible plastic cylinders in turn enclosed inside a double layer of steel rings which overlapped each other and gave a tough yet flexible armouring. Each repeater was about two and a half metres long and seventy millimetres in diameter

which was twice the diameter of the cable (thirty-two millimetres). Built into a cable in advance, the repeaters could bend round the sheaves of the paying-out machine, and the cable-laying ship could forge ahead non-stop.

In 1948, a 37-kilometre cable complete with intermediate repeaters was laid on an experimental basis near the Bahama Island at a depth down to 3700 metres, and in 1950 two 3.52/12.7 cables each equipped with three flexible repeaters were laid between Key West and Havana over a distance of over two hundred kilometres and at a depth close to a nautical mile.

In 1952, design work started on the first Atlantic telephone line, and in 1954 the manufacture of cables for it began. The two-cable line was installed in two steps: at first, one cable was laid in 1955, and then the other cable in 1956. The line was officially placed in service on September 25, 1956, ninety years and two months after a permanent telegraph service was set up across the Atlantic. Thirty-three years have passed since then. The line today does not look impressive at all, but in 1956 it had a far-reaching technical, economic and psychological impact.

What cable technology and electronics did together in the 1950s can hardly be overestimated even today. It is often asked: Can it really be true that there was no telephone communication between Europe and America before the 1956 line was installed? No, there was none – prior to 1928. In 1928, radiotelephone services became available, mainly on short waves. Unfortunately, radio communication is prone to blackouts which may persist for several days on end because of atmospheric noise and interference. What is most important, however, was the fact that, under international frequency allocation, only fourteen channels were made available for communication between Great Britain and the United States and a mere two channels between Great Britain and Canada.

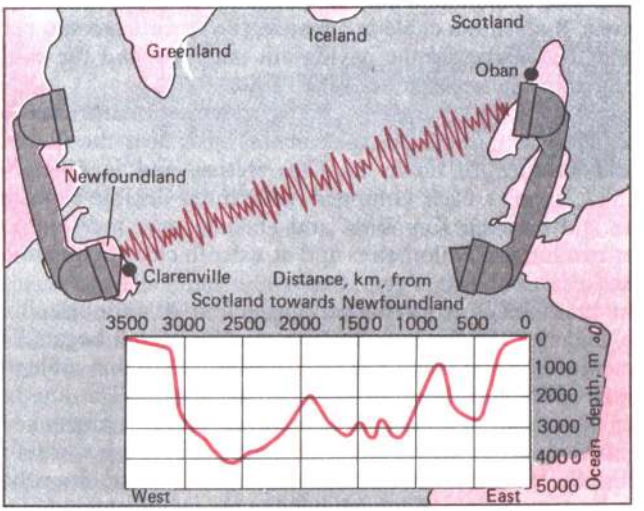


Fig. 8.2. Transverse profile of the ocean floor along the deep-water section of TAT-1

The first Transatlantic telephone line, TAT-1 for short, had twice as great a capacity – it could carry thirty-six channels: twenty-nine channels between London and New York, six channels between London and Montreal, and the remaining channel was used for multichannel telegraphy and maintenance purposes. Later, TAT-1's capacity was increased to seventy-six channels owing to a better use of its circuits. The most important thing was that the line had proved that it was quite feasible – both in principle and in practice – to provide telephone communication over cables spanning distances of several thousand kilometres, to install cables complete with repeaters at depths of several thousand metres, and to

maintain the continuity of service for practically any length of time and in any part of the system.

The 'vital statistics' of TAT-1 now belong to history. Yet, it is worth while recalling some of the data. The line had three sections: a deep-water section between Oban, Scotland and Clarenville, Newfoundland, spanning a distance of 3620 kilometres; a short-haul land-based hundred-kilometre section crossing Newfoundland from Clarenville to Terrenceville; and a shallow-water 510-kilometre section from Terrenceville to Sidney Mines in Nova Scotia. From Sidney Mines, messages were relayed to New York and Montreal over land-based coaxial cables and by radio links.

The inner conductor of the 4.1/15.75 cable used in TAT-1 was a copper wire 3.36 millimetres in diameter, topped by three copper 'surround' tapes 3.76 millimetres wide and 0.37 millimetres thick, wound with their edges touching. The inner conductor was encased in polyethylene insulation 5.8 millimetres thick, to which five per cent polyisobutylene was added to avoid cracking in seawater. The outer, or 'return', conductor was a helix of six copper tapes 8.1 millimetres wide and 0.41 millimetre thick, held together by copper tape 44.4 millimetres wide and 0.8 millimetre thick and polyethylene

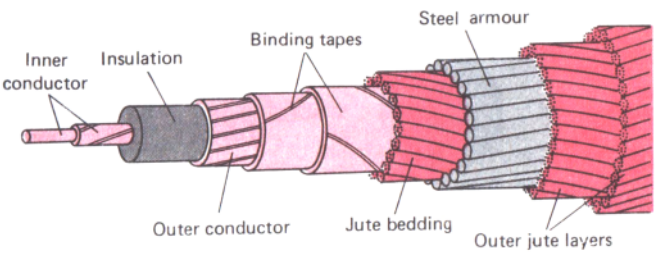


Fig. 8.3. First deep-water transatlantic cable for carrier telephony

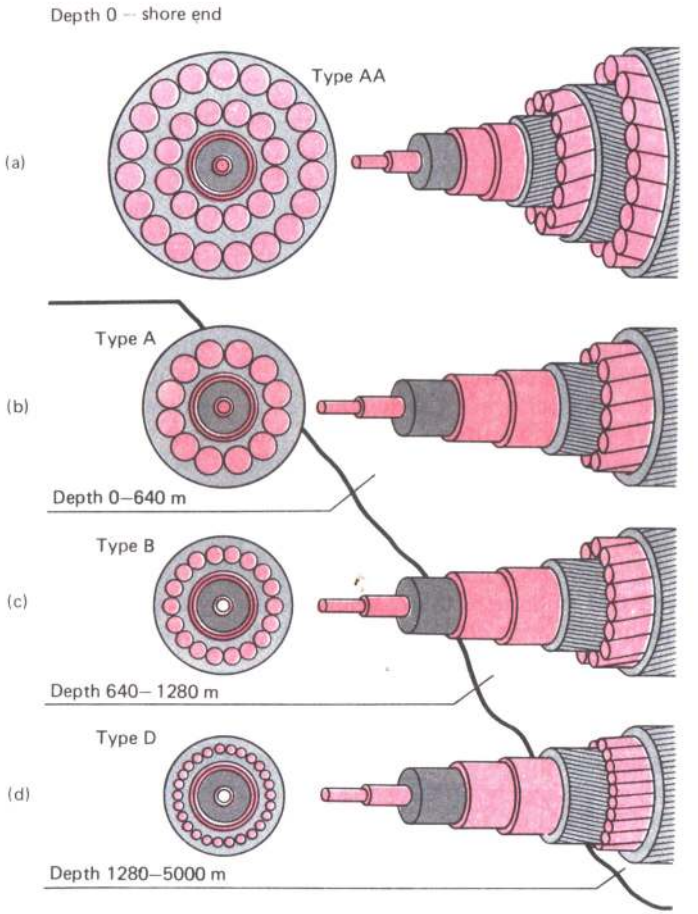
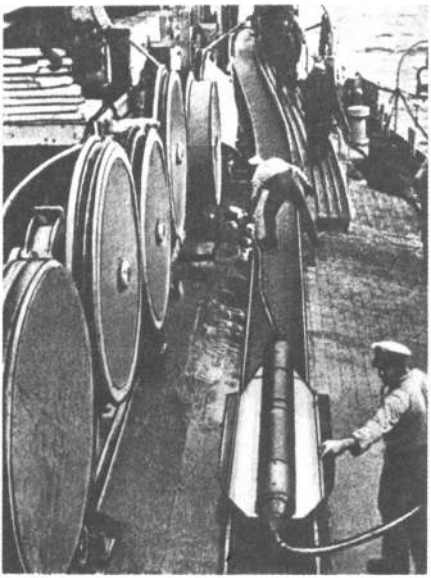


Fig. 8.4. Armouring for the underwater cables installed in the 1950s: (*a*) shore ends; (*b*) shallow-water; (*c*) medium-depth; (*d*) deep-water

Table 15. Armouring of Cables Used in TAT-1

Cable type	Depth installed, m	Armour type	No. & dia. of armour wires, mm	Outside dia. of cable, mm	Cable weight per unit length, tonne/km
Shore ends	0	AA	12 × 7.6 + 19 × 7.6	67	18
Shallow-water	0-640	A	12 × 7.6	48	6.5
Medium-depth	640-1280	B	18 × 4.2	36	3
Deep-water	Over 1280	D	24 × 2.2	32	1.7



(a)

Fig. 8.5. Submarine (or submersible) repeater: (*a*) passed around a cable-laying machine; (*b*) at entry into the water

tape. Four armour types were used, depending on service conditions. The shore ends of the cable additionally had an electromagnetic shield made up of steel tapes applied in five consecutive layers.

The main, or deep-water, section operated as a two-cable system. The two cables were laid forty kilometres apart and each was used for transmission in one direction only, in the frequency band 20-164 kilohertz. The shallow-water and shore sections operated as single-cable systems, with the two direct-

(b)

Fig. 8.5. (*Continued*)

ions of transmission separated on a frequency basis, the traffic bands being 20 to 260 kilohertz in one direction, and 312 to 552 kilohertz in the other, offering a total of sixty channels. The gain of the repeaters at the highest frequency was sixty decibels, and the cable attenuation at 164 kilohertz was about 0.9 decibel. Therefore, the repeaters within the deep-water section needed to be spaced seventy kilometres apart.

Each cable had fifty-one one-way tube repeaters. Since they used vacuum tubes for their amplifiers, they needed d. c. supply voltages for their anode and filament circuits. These were fed from supply sources located at the shore-based terminal stations. The inner conductor of the cables used in TAT-1 was connected to a + 2.3 kV terminal at one end and to a − 2.3 kV terminal at the other. The 'return' part for the supply circuits was seawater.

As a saying goes, the first step is the hardest, and it had been made. As newspapers wrote on the occasion, one of the twentieth-century miracles had become a common thing. The ensuing years saw an explosive growth of transoceanic submarine telephony. Although TAT-1 nearly doubled the capacity of telephone service between Europe and the United States as compared with the thirty years of radio telephony, the shortage was felt almost immediately. Indeed, the appetite comes with eating! Four more transoceanic two-cable lines were laid in the latter half of the 1950s, including one between San Francisco, USA and Honolulu, Hawaii in the Pacific, and another from Pont de Penmarch, France and Clarenville, Newfoundland, which came to be named as TAT-2 and went into operation in 1959.

At the same time, a good deal of effort was put into the development of deep-water, single-cable systems using two-way repeaters enclosed into tubular housings four metres long and seventeen centimetres in diameter. In 1957, a single cable eighty hundred and ninety kilometres long was laid between

Marseille, France and Algiers, Algeria. Installed at a depth of over two and a half kilometres, it used twenty-eight two-way repeaters and provided sixty communication channels.

Along with the cables themselves, improvements were made in cable-laying facilities. A five-sheave machine was designed and a cable-laying technique was devised with which rigid repeaters didn't have to bend round the sheaves. Instead, a so-called 'bypass' cable attached ahead of and behind each repeater section was passed over the sheaves, and the repeater sections bypassed the machine, with the repeaters carried on a trolley riding a rail track.

MINUS THE ARMOUR

The event that tipped the scales in favour of single-cable underwater systems less expensive to build than their double-cable counterparts was the advent of armourless cables – an entirely new approach to cable construction. First used on the Dover-Calais submarine cable in 1851, the iron wire armour was viewed as an indispensable component of all underwater cables for a whole century. It was simply unthinkable to use a cable without an armour. And now, in 1951, or exactly a hundred years after the armour had made its first appearance, the British engineer Robert Alston Brockbank proposed to abandon it. He applied for a patent on August 16, 1951, and soon was issued British patent No. 703782 for a new type of deep-water cable.

The invention sealed the fate of armoured deep-water cables and ushered in the age of armourless cables. The puzzled reader may ask, "Why? Could it be that cable users were wrong about the armour?"

Let's recall how the cable armour came into being. The first submarine telegraph cable which crossed the English Channel

in 1850 was torn by a fisherman just a few hours after it had been installed. All the succeeding cables were protected by an armour of iron wires, and no harm could come to them from fishing trawls, ships' anchors, or chafing against rocks as the sea changed from a low to a high tide or back. But all of these dangers can threaten only the shore ends of a cable and cables laid in shallow water. At a depth of several kilometres, the cable is beyond the reach of any trawl, anchor or whatever it may be. It lies quietly on the soft silt bed and is gradually buried in more silt on top. Nothing seems to be able to trouble the cable's life. Why is it then that a deep water cable needs an armour after all? It may sound a bit extravagant, but a cable needs its armour for just a few hours when it is being paid out and, sometimes, should a need arise to bring it to the surface for repair.

This works out to a few hours of use and decades, or several hundred thousand hours, of idleness. Still, deprived of steel armour wires, a cable wouldn't be able either to enter or leave the immense depths of the ocean. It is these wires that safeguard the cable section a few kilometres long, hanging free between the cable-laying ship and the ocean floor, against breaking under its own weight. Let's prove the point by making simple calculations. The density of copper is close to nine tonnes per cubic metre (or nine grams per cubic centimetre). One kilometre of copper wire with a cross-sectional area of one square millimetre has a mass of nine-thousandths of a tonne, or nine kilograms, and so its weight is about nine kilograms in air and eight kilograms in water. The tensile strength of soft-drawn (annealed) copper is twenty-eight kilograms per square millimetre. A free hanging length of copper wire will not break under its own weight until this weight is less than its tensile strength. In water, this length is three and a half kilometres. A longer piece of copper wire will snap.

The above figures hold, however, when everything is quiet.

Actually a transoceanic cable is laid from a moving ship, sometimes in a stormy weather. Hanging from the ship's stern, the cable has to stand up to tugs and pulls with a force greatly in excess of what can come from its own weight. Recall how many times the first transatlantic cable was broken during a decade's attempts to install it. There is the added weight of the polyethylene insulation applied to the copper conductors.

How could a cable possibly be lowered to a depth of four to five kilometres or even more? That was where the steel armour came to rescue. The density of steel is seven and eight tenths of gram per cubic centimetre, and the tensile strength of steel armour wires is 150 to 200 kilograms per square millimetre. One kilometre of steel wire with a cross-sectional area of one square millimetre has a weight of about eight kilograms in air and seven kilograms in water. This means that, when placed in water, it can stand up, without bursting, to the weight of twenty-five kilometres of wire. This is more than enough not only to reach the lowest oceanic depth (eleven and a half kilometres), but also to provide a good margin of safety.

It was the armour that was, during a century, the only support for the huge weight of the cable paid out from a ship, and safeguarded it against snapping. Still, it is extremely vexing to put an armour on a cable only in order to deliver it safely to the oceanic floor. Indeed, after a cable has been laid on its deep-water bed, its armour becomes altogether unnecessary for many years, mostly for ever. That is a sheer waste of capital! And a huge one, at that! On average, the steel armour weighs as much as all the other elements of a cable taken together. This means that only half of the armour's load-bearing capacity is utilized to support the core, and the other half goes to support the armour's own weight. A vicious circle, indeed!

Most importantly, the weight of the armour used on one kilometre of deep-water cable is about a thousand kilograms.

A total of over a million kilometres of underwater cables have been installed to date. This means that over a million tonnes of high-quality steel wire is idling at the floors of seas and oceans.

But there is more than that. The armour complicates the cable-laying operation. Steel wires are applied to a cable as a helix wound either clockwise (a right-hand spiral) or counter-clockwise (a left-hand spiral). When a great length of cable is being paid out, as would be the case in the open Atlantic, stopping the ship introduces very serious danger of kinking. The spiral of armour tends to untwist slightly when the cable hangs freely down from the ship's stern. When the paying-out is steady and continuous, this untwisting spreads itself uniformly along the cable without causing any harm. But stopping the ship can result in kinks which may distort the cable or even tie it in knots. This kinking is especially dangerous to cables with built-in repeaters. That was why two-way repeaters in rigid capsules couldn't be properly installed at large depths for many years: as the cable touched the oceanic floor, it would break loose at the point of entry into a repeater. The only remedy would seem to apply another layer of armour wound in the opposite direction to the first. This would, however, have added to the cost and weight of the cable and would have complicated its manufacture and installation still more.

Brockbank's ingenious idea came as another brilliant example of engineering beauty in the cable-making art. He took notice of skin effect – the crowding of current to the periphery of a conductor at high frequencies, and suggested that the inner conductor should be a copper tape formed into a tube and locked by a box seam along the length of the cable. The strength of the cable was to be enhanced by a strength member – a core of steel strands surrounded by the inner conductor – it was to supply the support previously provided by the armour. Since the strength member is lighter in weight

than the armour outside the cable, the new design has finally come to be known as light-weight cable. In this author's opinion, the name 'armourless' is more befitting.

Since, in contrast to the armour, the strength member consists of many strands, it is an easy matter to choose their diameters and also the direction and pitch of twisting so that the cable's tendency to form kinks can fully be balanced out and the cable complete with its rigid repeaters can be paid out non-stop to any depth.

Armourless cable is more attractive than its armoured counterpart in many respects. Among other things, it has a smaller outside diameter and a smaller weight due to the omission of armour. Or, given the same outside diameter, it has a lower attenuation because it uses a larger coaxial pair which has, therefore, a lower resistance and needs only a polyethylene sheath.

As a try-out, a hybrid cable, that is one having both a strength member and an armour, was installed in 1960 on the 980-kilometre line between Sweden and England from Göteborg to Marske (approximately ten miles north of Middlesbrough). In 1961, the first truly armourless telephone cable was installed (and is still being used) in the Commonwealth round-the-world telephone cable scheme which starts with the CANTAT-1 cable linking Great Britain with Canada via Newfoundland. In 1962-1963, a 15 000-kilometre cable line, known as the COMPAC Cable, was installed in the Pacific, running from Vancouver, Canada, via Hawaii, the Fiji Islands and New Zealand to Sidney, Australia. This scheme uses armourless telephone cable over ninety-five per cent of its length, the remaining five per cent being built with armoured cable laid at depths less than seven hundred metres.

What was the early armourless telephone cable like?

Let's take the American SD 8.4/25.4 cable as an example. It had a strength member made up of forty-one strands in five

different diameters (from 0.8 to 1.9 millimetres) formed into three layers all wound in the same direction. The strength member with an outside diameter of 7.4 millimetres was surrounded by the inner conductor made of copper tape 0.6 millimetre thick. After the inner conductor was formed into a tube encasing the strength member, its seam running the entire length of the cable was welded with an electric arc in an argon-helium atmosphere. After the seam was welded, the inner conductor was swaged so that it fitted tightly around the strength member. The inner conductor was wrapped with a polyethylene insulation to an external diameter of 25.4 millimetres. The outer conductor was a copper tape applied longitudinally and topped by a polyethylene sheath to an outside diameter equal to that of an armoured cable with a smaller coaxial pair, that is, 4.1/15.75.

In the British modification of the 8.2/25.2 armourless telephone cable, the strength member was made up of forty-three strands likewise applied in three layers over the central strand (this may be designated as a 1 + 6 + 12 + 24 design), but wound in alternate directions. The inner conductor was a copper tape 0.3 millimetre thick. In contrast to the American SD cable, the British Mark-1 cable had an outer conductor made up of six aluminium tapes wound as a single-layer helix. This reduced the weight and increased its breaking length in water but, coupled with a thinner internal conductor, somewhat impaired the electrical parameters of transmission as compared with its American counterpart – its attenuation was by twelve to fifteen per cent greater.

Sometimes the strength member of an armourless telephone cable is described as its central conductor encased in a copper-tape braid. This description is inaccurate on at least two points. Firstly, the copper tape used to make the inner conductor is not a braid. No underwater cable has ever used any kind of braiding. Braiding does find use in flexible cables,

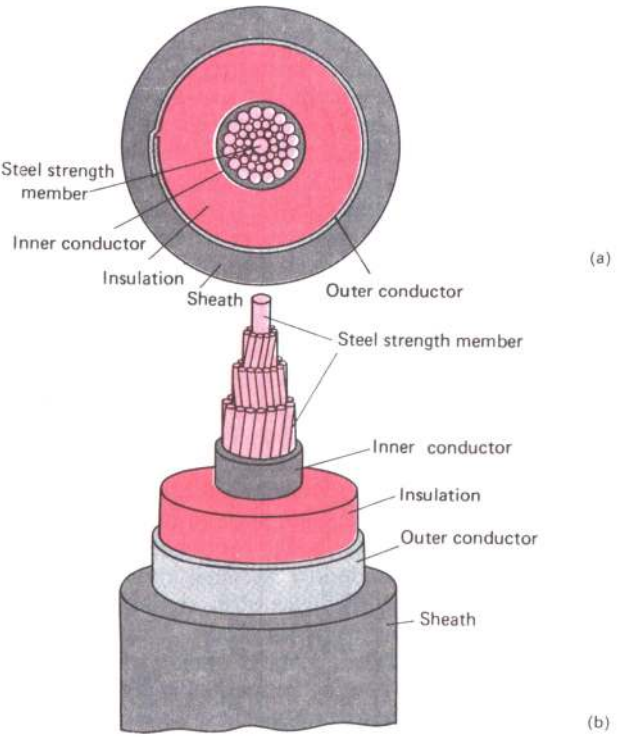


Fig. 8.6. Armourless (or light-weight) telephone cable: (*a*) cross-sectional view; (*b*) external appearance

and not in telephone cables for permanent, fixed installation, and the braid itself woven from fibres or wires and not from tapes. Secondly, the steel core is not a conductor – it is a stress-taking element intended to resist mechanical loads. The

Table 16. Armoured and Armourless (English) Deep-Water Coaxial Cables

Cable type	Load-bearing member	Insulation diameter, mm	Outer diameter, mm	Weight, kg/km		Tensile strength, kg/mm^2	Breaking length in water, km	Attenuation constant at frequency 608 dB/km
				in air	in water			
With armour 4.1/15.75	24 × 2.2 mm	15.75	32.2	1700	980	12 700	13	1.73
With strength member 8.2/25.2	19 × 1.2 +24 × 0.8 mm	25.2	33.0	1210	330	7600	23	1.14

inner conductor is the copper tube encasing the steel core all along its length.

Since Brockbank's invention, effort in the field of underwater communication systems has mainly been put into further improvements in the design of armourless telephone cables and into the use of ever higher frequencies for telephone traffic. Of all the wire communication lines, the highest pace of advance up the frequency (f) scale in the past twenty-five years has been shown by underwater lines. As a way of increasing the number of channels available to telephony over transoceanic and undersea cables, it was agreed in the 1960s (and the agreement is still in force) that the traffic bands should be three (instead of four) kilohertz wide and that the voice frequencies to be transmitted should extend from 200 to 3050 hertz. Although somewhat degraded, the quality of service has remained quite satisfactory, but the efficiency of extremely expensive long-distance systems has gone up by a third because the traffic-handling capacity of the lines increased in a four-to-three ratio through the replacement of terminal equipment alone – the basic groups of twelve channels four kilohertz wide each have been replaced with basic groups of sixteen channels three kilohertz wide each. Thus, the increase in the number of channels has been achieved without exceeding the previous total frequency range. Accordingly, TAT-1 and TAT-2 which previously operated on a thirty-six channel basis have been switched to forty-eight channel operation.

The years 1961 through 1965 saw a major advance in the maximum traffic frequency from 0.16 megahertz to 0.6 megahertz and, finally, to one megahertz. Naturally, this had brought with it an increase in cable attenuation, and a need arose to halve the repeater spacing. To maintain an adequate power feed to the greater number of series-connected intermediate repeaters, the d.c. voltage supplied by the shore-based batteries was raised from two or two and a half kilovolts to

seven kilovolts. This rise in supply voltage became possible with the development of an especially pure polyethylene insulation which had lower dielectric losses and a higher dielectric strength.

The maximum number of repeaters that could be put on a line was raised to one hundred and eighty-five, and this offered the possibility of installing cables directly from Europe to the United States without relaying via Newfoundland. Among them were TAT-3, a 128-channel system spanning a distance of 6500 kilometres from Great Britain to the United States and built in 1963; TAT-4, also a 128-channel system 6650 kilometres long, built in 1965; and TRANSPAC, a trans-Pacific line installed in 1964 from the United States, via Honolulu (Hawaii), the Midway Island, the Wake Island, and the Guam Island to Japan.

The next step up the frequency scale was prompted by the replacement of vacuum tube repeaters with their transistorized equivalents. With a power drain one-fifth to one-tenth as large, as many as four hundred repeaters could now be put on a cable line. After ten submarine lines carrying from 420 to 720 channels each were installed in 1970, the United States was linked to Spain by TAT-5, a 6400-kilometre system. It could carry 845 telephone conversations at a time over a frequency band of six megahertz. Because of this increase in traffic bandwidth, the diameter of a coaxial pair (as measured over the insulation) was also increased to just over thirty-eight millimetres, and the outside diameter of the armourless telephone cable went up to forty-four and a half millimetres. With the repeaters spaced nearly nineteen kilometres, a reliable telephone service could be maintained over a distance of 7400 kilometres. The cost per channel-kilometre in TAT-5 was one-sixteenth of its figure in TAT-1.

In the 1970s, the diameter of an underwater coaxial pair was further increased to 43.2 millimetres, and the traffic bandwidth

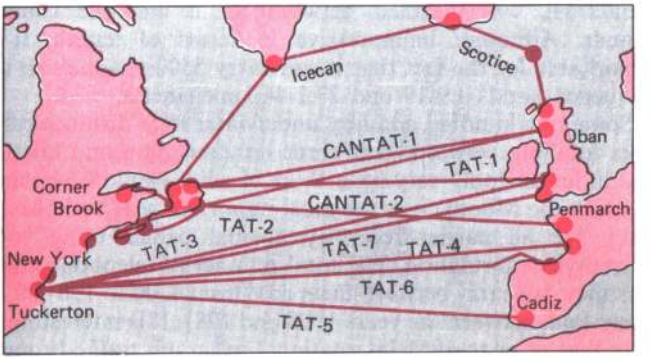


Fig. 8.7. Transatlantic telephone cable routes in the Northern hemisphere

was extended first to 12-14 megahertz, then to 25-30 megahertz, and finally to 36-45 megahertz, with the repeater spacing reduced to twelve, nine and six kilometres, respectively.

In 1974, CANTAT-2, a 1840-channel cable line, linked Great Britain with Canada, and in 1976, TAT-6, a 4000-channel cable line, connected the United States and France. Its traffic handling capacity was 111 times that of TAT-1 in 1956. Indeed, any of the transatlantic cable lines built in the 1970s exceeded in its capacity and performance all the previous lines taken together.

When, in 1978, TAT-1 was removed from service after twenty-two years of trouble-free operation, it accounted for less than one per cent in the total traffic handling capacity of all the transatlantic cables. This explains why, in contrast to its inauguration, removal of TAT-1 from service passed unnoticed by the public. That was perhaps unjust to the line – it did deserve a good word for what it had done.

In 1977, PENCAN-3, a relatively short link (by transatlantic

standards), was installed between Spain and the Canary Islands. Although unimpressive in terms of length, it is remarkable for the fact that it can carry 5500 channels in the frequency bands 1.9-19 and 27.2-44.3 megahertz.

Some two hundred and fifty underwater long-distance cable lines totalling between them three hundred thousand kilometres in length (only very little short of what would be enough to reach the Moon) cross the most important seas and oceans. They are all carrier-frequency coaxial cables using solid polyethylene insulation. The total number of telephone channels they can carry between them rose from 4200 to 136 000, or thirty-fold, between the years 1965 and 1981. It is interesting to note that prior to 1951 international telegraph traffic brought in more money in revenue than did international telephone traffic. Between 1951 and 1978, however, the share of the revenue from telephone services went up from twenty-two per cent to seventy-one per cent.

Table 17. Transatlantic Telephone Cables

Name	Year of construction	Countries linked	Nominal number of 3-kHz channels
TAT-1	1956	Britain-USA	48
TAT-2	1959	France-USA	48
CANTAT-1	1961	Britain-Canada	80
TAT-3	1963	Britain-USA	128
TAT-4	1965	France-USA	138
TAT-5	1970	Spain-USA	845
CANTAT-2	1974	Britain-Canada	1840
TAT-6	1976	France-USA	4000
TAT-7	1983	Britain-USA	4000

Table 18. Generations of Transoceanic Carrier-Frequency Coaxial Cables and Multichannel Systems

Years	Generation	Cable type	Diameter, mm			Number of 3-kHz channels	Traffic frequency band, MHz
			core	conductors			
				d	D		
1956-1960	First	Armoured	—	4.1	15.75	48	0.16
1961-1965	Second	Light-weight	7.4-7.6	8.0-8.4	25.2-25.4	128-360	1-3
1966-1975	Third	Same	7.4-7.6	8.0-8.4	25.4-38.1	640-845	5-6
						1600-1840	12-14
1976-1985	Fourth	Same	8.4-8.5	9.2-9.4	43.2	3440-5520	25-45

Much as the early underwater single-conductor cables stimulated the growth of the world-wide telegraph network in the latter half of the nineteenth century, so the coaxial cables of the mid-twentieth century have offered an answer to the problem of global telephone communication in our days.

In the early 1970s it was predicted that in the 1980s underwater long-distance cable lines would provide ten to fifteen thousand channels. However, as has been the case with underground communication cables, telephony has set its sights on underwater optical fibre cables first tried in the early 1980s.

To sum up, three phases may be singled out in the history of underwater communication cables, spanning between them a period of one hundred and forty years. These phases are outlined below.

Phase I: 1850-1900. Undersea and transoceanic single-conductor telegraph cables using gutta-percha insulation.

Phase II: 1900-1950. Undersea telephone cables without intermediate repeaters. 1900-1930, voice-frequency balanced cables using gutta-percha and air-space insulation. 1930-1950, carrier-frequency coaxial cables using paragutta (in the 1930s) and then polyethylene (in the 1940s) as insulation.

Phase III: 1950 to our days. Carrier-frequency undersea and transoceanic cables using solid polyethylene insulation and intermediate repeaters.

Phase III may conveniently be divided into three periods. The first, and the shortest of all, began in 1950 and ended in 1956. It was the time of undersea lines from a hundred to six hundred kilometres long with one to seven vacuum tube repeaters, depending on the length of a line and the frequency spectrum involved. The second period began in 1956 and ended in 1968. It

was the time of an explosive growth in the construction of oceanic and transoceanic links up to 6500 kilometres long with as many as 185 vacuum tube repeaters per line. At first, armoured deep-water cables prevailed, but later, beginning in 1961, they were replaced with armourless telephone cables. The third period, from 1968 to our days, features the use of several generations of armourless telephone cables and transistorized repeaters.

Nowadays we are entering a fourth phase – one of optical cables.

Chapter Nine

A Look at the Future

A RIVALRY WITH NO END

Man is not very consistent in his stand towards communication cables. On the one hand he recognizes that he needs them and admires their growing capabilities. On the other, he feels vexed over the fact that so much material has to be buried in ground or under water to lie 'idling' for decades.

Indeed, an electric motor runs, the finger plate of a telephone spins, a line finder at a telephone exchange moves, and only the cable lies seemingly idle.

There is no denying – it takes a lot of materials to make cable. This is why wireless, or radio, communication was immediately hailed as a mighty rival for wire communication.

In a lecture on submarine telegraphy at the Imperial Institute in London on February 15, 1897, Professor William Ayrton, a British electrician of some renown, made an extraordinary prediction: "There is no doubt that the day will come... when copper wires, gutta-percha coverings and iron sheathings will be relegated to the Museum of Antiquities. Then, when a person wants to telegraph a friend..., he will call in an electromagnetic voice which will be heard loud by him who has the electromagnetic ear. ... He will call 'Where are you?' and the reply will come...".

The second part of his prediction has come true completely. Radio communication, among the most outstanding achievements of the twentieth century, is serving man in many capacities. As to relegating cables to a museum, Professor Ayrton has proved wrong. Although every new advance in radio communication has cast doubt on the further existence of cables or has seemed to deprive them of any prospects, both

forms of communication – wire (or cable) and wireless (or radio) – have remained rivals for nearly ninety years now, see-sawing between success and failure in turn.

The history of their rivalry is among other things illustrated by progress in intercontinental transoceanic communication. As will be recalled, telegraph cables were the first to cross the Atlantic, but we will leave them out because radio was yet to be invented at that time. Radio spanned the Atlantic on December 12, 1901, when over a dozen underwater cables had been installed between the Old and New Worlds. Using a wire antenna attached to a kite sent aloft not far away from the town of St. John's, Newfoundland, Marchese Guglielmo Marconi (1874-1937) received a radiotelegraph message sent from Poldhu in Cornwall, England. The message consisting of a single letter 'S' – three dots in the Morse code – was radioed at a wavelength of 915 metres (a frequency of 328 kilohertz).

Nevertheless, telegraph traffic in the first quarter of the twentieth century was mainly handled by underwater cables. The first round was theirs. The more so that the first commercial radiogram wasn't sent across the Atlantic until March 1, 1920.

But radio communication won the next round. That was the time when transoceanic radiotelephony held an undivided supremacy. Even fifty years after Bell's invention, there was no way of sending a telephone call from Europe to America, although close on nineteen million telephones were in use in the United States and eight million in Europe at that time.

In February 1927, the first public radiotelephone line went into operation between London and New York. It operated at a wavelength of about six kilometres. (For the sake of historic truth it should be admitted that speech was first transmitted across the Atlantic by US Army radio operators on October 23, 1915 from Arlington, Virginia, and received at the Eiffel

Tower, Paris.) Before long, preference was given to the shorter wavelengths (higher frequencies) as more efficient. And immediately the need for further improvements in underwater cable lines was questioned.

Despite the thirty years or so of transoceanic radiotelephony's monopoly, however, cable technology didn't lay down its arms. The inauguration of TAT-1 in 1956 opened the third round of the bout in which the supremacy went to underwater telephone cables. Lasting for a decade, this supremacy was based on both the larger traffic handling capacity and the greater total length of cable lines. Between the years 1956 and 1965, the daily telephone traffic between the Britain, on one side of the Atlantic, and the United States and Canada on the other increased from 407 to 3831 telephone calls, that is, nine- or ten-fold.

It would seem that transoceanic cable links had undoubtedly bright prospects before them. However, barely a year had passed since the official inauguration of the first transatlantic telephone cable line when an epoch-making event occurred in the world: on October 4, 1957, the Soviet Union put in orbit around the Earth the world's first artificial satellite. This event ushered in a new age – the space age. A few years later, communication satellites were orbited on an experimental basis. At first, they were passive satellites which reflected the signals sent from Earth-based transmitters in all directions in a mirror-like fashion. They were followed by active communication satellites which carried all that is necessary to receive, amplify and re-transmit radio signals in any required direction.

Commercial communication satellites went into operation in 1965. On April 23, 1965, the Soviet Union launched *Molniya-1,* its first active communication satellite. A bit earlier, on April 6, 1965, the United States launched its *Early Bird,* or *Intelsat 1.* From the outset, communication satellites outper-

formed underwater cables in the number of channels that they could carry. For example, *Early Bird* could carry two hundred and forty two-way voice (telephone) channels and was designed to handle all types of communications traffic, including television between North America and Europe. In contrast, the contemporary transoceanic cables could support one hundred and twenty-eight channels, and undersea cables, one hundred and sixty. This again cast doubt on whether it was worth while spending effort and money on further improvements in underwater cable lines. Their days seemed to have been counted. Nothing of the kind has however happened – the fourth round still in progress is a display of stiff competition between cable and satellite intercontinental communications systems in terms of performance and cost.

About the same competition could be seen on land. My generation still remembers the public disputes on which systems to prefer – cable or radio-relay?

It may sound paradoxically, but it is a fact that every advance in radio communication led in the final analysis to a faster pace of progress, rather than to rejection, of cables. The rivalry has obviously been beneficial to the cable-making art. That much can be seen from the headlines that the technical journals carried at the time: "Battle between Cables and Satellites", "Cables Accept Satellites' Challenge", "Cables Defeat Satellites". As follows from Table 19, the number of telephone channels carried by satellite communications systems increased between 1965 and 1980 fifty-fold; cable technology didn't leave the challenge unanswered: the number of channels on cables increased forty-three times in the same period.

An unquestionable advantage which satellite communications systems offer over their submarine cable counterparts is the fact that they can handle all types of communication traffic, including television. Another advantage is that one

Table 19. Growth of Telephone Channels Carried by Submarine Cables and Satellite Systems

Year	Submarine cable line		Communications satellite	
	name	number of channels	name	number of channels
1956	TAT-1	48	—	—
1961	CANTAT-1	80	—	—
1962	COMPAC	80	—	—
1963	TAT-3	128	—	—
1964	TRANSPAC-1	128	—	—
1965	PENCAN-1	160	Intelsat 1 (Early Bird)	240
1966	—	—	Intelsat 2	240
1968	SAT-1	360	Intelsat 3	1200
1970	TAT-5	845	—	—
1971	PENCAN-2	1840	Intelsat 4	5000-6000
1974	CANTAT-2	1840	—	—
1976	TAT-6	4000	Intelsat 4a	6000*
1977	PENCAN-3	5520	—	—
1980	—	—	Intelsat 5	12000*

* Plus two TV channels.

satellite can be used for transmission in tens of directions. In contrast, a transoceanic cable line links only two points at its ends where it is connected into a land-based transcontinental network. Nevertheless, ten per cent more capital was invested in submarine cable projects between 1962 and 1978 than in satellite communications systems. By the early 1980s, the cost of one telephone channel carried by a submarine cable was one-quarter of the figure quoted for satellite communications systems. This is because a submarine cable has a service life of

twenty-five years as against the seven years that a communication satellite remains, on average, in service. Also, maintenance costs for cable lines are markedly smaller than they are for satellites. Every year a cable loses four per cent in its value (what is financially known as depreciation) as against the fourteen per cent lost by a satellite. The operating costs are one and ten per cent, respectively.

At this writing, forty to forty-five per cent of all communications traffic between Europe and America is handled by satellites and fifty-five to sixty per cent by transatlantic cables. We may safely say, therefore, that the current round has brought the bout between them to a tie.

The heel of Achilles for both underwater and, especially, underground cables is the fact that huge amounts of materials are needed to make them. Man doesn't want to and, indeed, can't reconcile himself to this mammoth waste of materials, above all the scarce copper and lead. True, the post-war years have seen a sizeable decline in the monopoly held by lead as the material for cable sheaths. Ever more ground is being gained by plastic sheaths, mostly made of polyethylene, and the less scarce metals aluminium and steel. Importantly, the corrugated aluminium or steel sheath, apart from replacing the hard-to-get lead, is a better performer.

As to copper wire, the current-conducting element of any communication cable, it is still being used practically alone and in very large quantities.

From very rough calculations based on indirect evidence it may be assumed that the underground, underwater and overhead communication cables now in service use about fifteen million tons of copper. All countries outside the Soviet Union produce between them seven to seven and a half million tons of copper every year. While the demand grows at a faster pace, it takes ever more labour and money to produce copper. For every

ton of copper smelted, nearly a hundred tons of copper-bearing ore have to be mined and processed. That's why ways and means are being looked for to save this ancient metal.

THE WONDER FIBRE

The first appearance. The idea to use glass fibre instead of copper conductors was first voiced about two decades ago. Today, the wonder fibre is all but a permanent feature in technical journals, and not only technical. It comes up ever more often in newspapers, popular-science and simply popular books, and is discussed on TV and radio programs. It is no chance that this author ended the three previous chapters with a mention of the promise to be held by fibre optical cables.

It is customary to date the history of light waveguides (sometimes called 'light pipes') back to John Tindal (1820-1893), a British physicist, mountaineer, brilliant experimentor, lecturer and science popularizer. In 1870, he demonstrated an ingenious experiment (Figure 9.1). He poured water in a vessel, *1*, fitted with a cock, *2*, and let it flow out in a solid jet, *3*, into a cup, *4*. A lens, *5*, built into the vessel just opposite the cock, focused the beam of light from an outside carbon arc, *6*, into the jet of water. Light propagated along the water jet by multiple internal reflection at the boundary between the water and air. In Tindal's experiment, the water jet appeared luminous all along its length. This principle is nowadays used to illuminate fountains with many colours.

As ray (or geometrical) optics tells us, a ray of light propagating in straight lines through a homogeneous medium, I, changes its direction at the interface between medium I and medium II, with some of the light returned back into medium I – a phenomenon known as reflection. If medium II is transparent, some light can pass across the interface with a change in its direction – a phenomenon known as refraction. The angles that

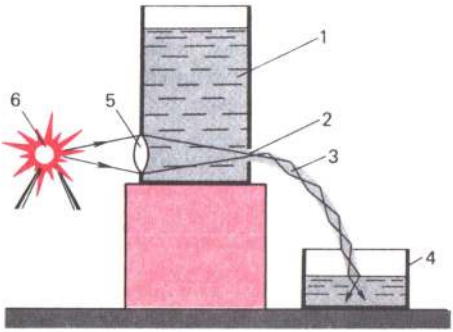


Fig. 9.1. Water light waveguide in Tindal's experiment, 1870

the incident, reflected and refracted rays make with the normal to the interface are respectively called the angle of incidence θ_{inc}, the angle of reflection θ_{refl}, and the angle of refraction θ_{refr}. The angle of incidence is always equal to the angle of reflection:

$$\theta_{inc} = \theta_{refl}$$

The law of refraction established in 1621 by the Dutch astronomer and mathematician Villebrood Snellius (1580-1626), and known today as Snell's Law is written

$$\sin \theta_{inc} / \sin \theta_{refr} = n_{II}/n_{I} = n_i$$

where n_I and n_{II} are the absolute refractive indexes of medium I and medium II with respect to a vacuum, and n_i is defined as

$$n_i = (\mu_{ai}\varepsilon_{ai})^{1/2}/(\mu_0\varepsilon_0)^{1/2} = (\mu_{ri}\varepsilon_{ri})^{1/2}$$

There is also what is known as the relative refractive index

$$n = (\mu_{rII}\varepsilon_{rII}/\mu_{rI}\varepsilon_{rI})^{1/2}$$

which relates two media (in our case medium II with respect to medium I).

As will be recalled, ε_0 is the permittivity of vacuum, ε_r is the relative permittivity, and $\varepsilon_a = \varepsilon_0 \varepsilon_r$ is the absolute permittivity of a material. Similarly, μ_0 is the permeability of vacuum, μ_r is the relative permeability, and $\mu_a = \mu_0 \mu_r$ is the absolute permeability of a material.

With media whose relative permeability, μ_r, is equal to unity, as is the case, for example, with glasses and polymers, the relative refractive index is equal to the ratio of the respective absolute or relative permittivities:

$$n = (\varepsilon_{II}/\varepsilon_I)^{1/2} = (\varepsilon_{rII}/\varepsilon_{rI})^{1/2}$$

A medium having a higher absolute refractive index is said to be more dense optically, and a medium having a lower absolute refractive index is said to be less dense optically. In passing from a more dense medium I (Figure 9.2) into a less dense medium II, that is, when n_I is greater than n_{II}, the ray of light may be totally reflected back into medium I without refraction. The angle of incidence, θ_{inc}, at which a total internal reflection occurs, is called the critical angle for total internal reflection, θ_{cr}:

$$\sin \theta_{cr} = n_{II}/n_I = n$$

This is because the angle of refraction is 90°, the ray grazes at the separating boundary, and the sine of θ_{refr} is unity. The refractive index of water is 1.33, and that of air is 1.0003, or approximately unity. In a water light waveguide

$$\sin \theta_{refr} = n_{air}/n_{water} = 0.75$$

and the critical angle for total internal reflection, θ_{cr}, is 48° 30′.

Thus, for a light wave to propagate from a more dense medium, n_I, without radiation into a less dense medium, n_{II}, it is essential that θ_{inc} be equal to or greater than θ_{cr}.

As the famous American physicist Robert Wood (1868-1955), 'a veritable virtuoso and wonder-maker of experimentation' (in the words of the Soviet scientist S. Vavilov), believed way back

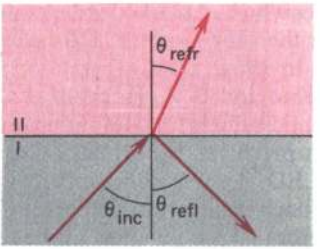


Fig. 9.2. A ray of light falling at the interface between two media

in 1905, light could be transmitted without an excessive loss of energy from one point to another by the use of total reflection from the walls of a rod made of glass or, still better, fused quartz. In fact, he had formulated the idea of a solid-state optical waveguide. Fifty more years were to pass, however, from its inception to implementation: it wasn't until the 1950s that what we know today as optical fibres consisting of a core and a cladding were made, with the core having a greater refractive index than the cladding, $n_{\mathrm{I}} > n_{\mathrm{II}}$.

Beginning in 1910, many ideas were put forward and more or less successful attempts were made to use glass rods and flexible glass fibres for the transmission of light over short distances. Gradually, optical waveguides found their way into medicine, cybernetics, light engineering, holography, instruments, nuclear engineering, and electron optics.

The advance of optical fibre communication systems was greatly stimulated by the invention, in 1960, of the laser (for *L*ight *A*mplification by *S*imulated *E*mission of *R*adiation) – a source of a narrow beam of light which is monochromatic, that is, of a single sharply defined wavelength or colour, and coherent, that is, with all its light waves travelling in step ('in phase'). The laser was the outcome of research done by N. Basov and A. Prokhorov of the Soviet Union, and by the American physicist

Charles H. Townes who had worked independently of his Soviet counterparts. For their invention, the three received the Nobel Prize for physics in 1964.

In 1966, S. K. Kao and G. A. Hockam of the United States proposed to use optical fibres for communication – transmission of the light beam produced by a laser or by a light-emitting diode (LED). A LED is a semiconductor device which produces a beam of monochromatic but incoherent light when a voltage is applied across its *p-n* junction in the forward direction.

Optical fibre communication systems use a relatively narrow range of optical frequencies (Figure 9.3). It includes visible light, the near infra-red, and part of the intermediade infra-red. In optics, as in radio engineering, it is more usual at such high frequencies to use the concept of wavelength:

$$\lambda = c/f$$

where c is the velocity of light in a vacuum, equal to three hundred million metres per second. The respective wavelengths that can, at least potentially, be used by optical fibre communications are 0.4 to 0.75, 0.75 to 1.5, and 1.5 to 3 micrometres. In practice, a narrow range extending from 0.6 to 1.6 micrometres is used at this writing.

At the sending end of an optical fibre communication system the electric waves carrying the intelligence that is to be transmitted are applied to an optical driver which modulates this intelligence upon the light emitted by a light source into the polished end of an optical fibre. At the receiving end the modulated light beam is picked up by a photodetector which is a silicon or germanium semiconductor device whose output signal varies in sympathy with the incoming modulated beam. Thus, this device converts the modulated beam into the electric signals that go to the recepient.

Here we have run into a paradox: the same glass, a classical dielectric used by F. Ronalds and B. Yacobi in the form of tubes

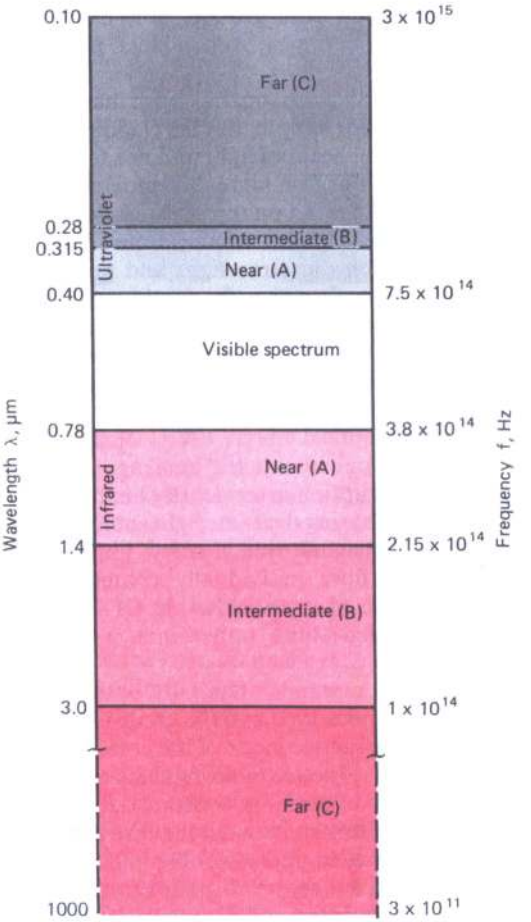


Fig. 9.3. Part of the electromagnetic spectrum

to insulate copper wire from ground, now has taken over as a sort of conductor. However, it 'conducts' photons and not electrons now.

We have learned that an optical fibre has a core and a cladding. It is important to note that the cladding only serves to reflect the propagating beam of light and not to give protection against mechanical injury or ingress of moisture. These latter jobs are done by coatings put on top of the cladding. In addition to protection against mechanical injuries and ingress of moisture, the coatings keep out stray light and prevent cross-talk between adjacent fibres. In a way, the coatings may be viewed as the insulation of an optical fibre, although not in the traditional sense of the word adopted in electrical engineering. After all, there are kinds of insulation other than electrical, for example, hydraulic, thermal, and sound insulation.

Instead of single optical fibres, use is often made of fibre bundles. In this way one avoids the breakage of the only fibre and the ensuing interruption in service. By bundling many fibres together, all of them sharing the same light source, many will still be able to carry the signal even if a few fibres break. These bundles, with each fibre individually coated and buffered, constitute the elements of an optical cable. Of course, there may be cables using a single fibre rather than a fibre bundle or bundles.

Where the optical fibre stands. Basically, optical fibres may be classed into the step index type and the graded index type. Here 'index' refers to the refractive index of the core. In a fibre with a step index profile the refractive index remains the same through a solid core (so that n_{I} remains constant) and only changes stepwise to n_{II} at the interface between the core and the cladding. In a fibre with a graded index profile the refractive index gradually decreases from centre to periphery until it becomes equal to that of the cladding at their interface (that is, where n_{I} equals n_{II}).

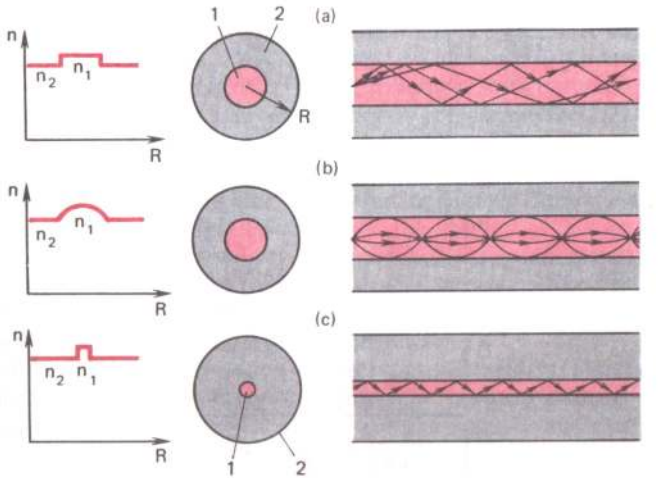


Fig. 9.4. Simple optical fibres: (*a*) step-index, multi-mode; (*b*) graded-index multi-mode; (*c*) step-index, single-mode; *1*, optical-fibre core; *2*, optical-fibre cladding

The transmission of light along an optical fibre heavily depends on the size of its core. The largest bandwidth is shown by fibres in which the core diameter d_c is comparable with the wavelength transmitted, that is,

$$d_c/\lambda \leqslant 10$$

For the wavelengths involved in optical communications, the core diameter ranges from eight to twelve micrometres. Such optical fibres can sustain only one mode of propagation, that is, only one particular field pattern in a plane transverse to the direction of propagation. Quite aptly, they are called single-mode fibres. With a core diameter of more than ten wavelengths, or over ten to fifteen micrometres, the fibre can support from

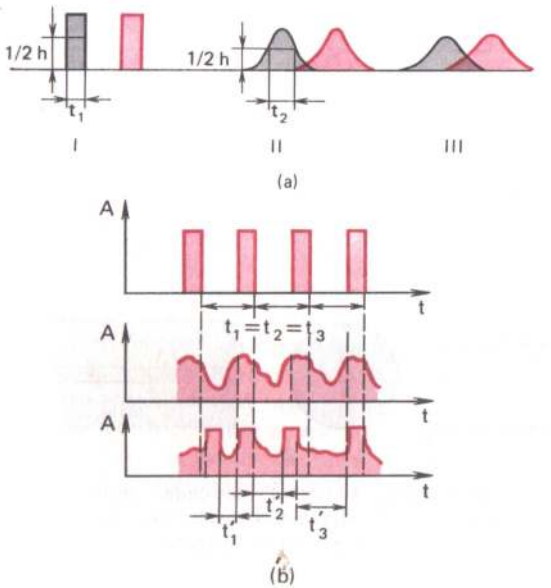


Fig. 9.5. Pulse dispersion in a fibre optic communication line (*a*): I, signal at the start of a line; II, same, in the middle of a line; III, same, at the end of a line and (*b*) change in time interval between pulses

tens to several hundred or even thousand modes. Those are multimode fibres.

Single-mode fibres offer far better conditions for light transmission than their multimode equivalents. Among other things they have a much lower attenuation and a lower dispersion (the broadening of the input pulse). Because of this, they have a broader bandwidth, that is, they can pass a wider range of frequencies. When taken together, all of these factors serve to extend the distance of optical fibre communication.

At present, however, graded-index fibres are the more common of the two types. They are easier to make and have a larger core which can readily be coupled to a light source; there is a wider choice of light sources themselves (which may be LEDs), and they lend themselves more readily to splicing.

Of the two types, graded-index multimode fibres are more preferable: they can support nearly half as many modes and the difference in propagation between the modes is markedly reduced – a factor serving to minimize pulse dispersion and to broaden the bandwidth. While step-index multimode fibres have a bandwidth of tens of megahertz, for graded-index multimode fibres the figure is hundreds of megahertz.

Broadband single-mode fibres have a bandwidth of several gigahertz. Unfortunately, their fine core is more difficult to make, and they need a stronger light source, such as a semiconductor laser, so as to make up for the losses suffered by the signal at entry to the optical waveguide. Also, the core measuring just a few thousandths of a millimetre in diameter is not so rugged mechanically.

Optical fibres are most often made of fused quartz – ultra-purified silica, SiO_2. In the course of fabrication (by one of several processes), as the core is precipitated from a $SiCl_4$ gas phase through an oxidation reaction

$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$$

within its cladding, some dopants, such as germanium oxide, phosphorus pentoxide or titania, are added in order to establish the desired difference in refractive index between the core and the cladding and the desired index profile – step or graded. Practically, the difference is small because n_I is as a rule equal to 1.525 and n_{II}, to 1.51. The critical angle for total reflection is close on 90 degrees:

$$\sin \theta_{cr} = 1.51/1.525 = 0.99737$$

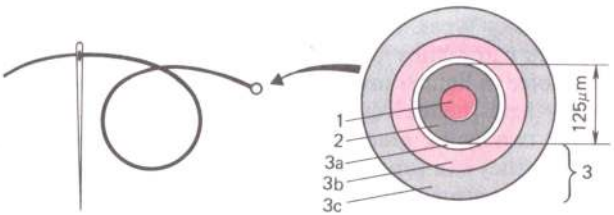


Fig. 9.6. Construction of an optical fibre: *1*, core; *2*, cladding; *3*, protective coatings: *a*, primary; *b*, buffer; *c*, outer

or

$$\theta_{cr} = 85°41'$$

It is usual to apply two or three coatings to an optical fibre. At first comes the primary coating located next to the core in the form of a film five to ten micrometres thick. Then comes a secondary or buffer coating (or jacket) of a silicon compound twenty-five to fifty micrometres thick. Finally, a third, or outer, coating of some polymeric material (such as polyethylene, polytetrafluoroethylene or polyamide) is applied by dip coating in solutions, extrusion, spray coating, or electrostatic coating to an outside diameter of 250 to 600 micrometres. As already noted, a coated optical fibre is an element of a fibre bundle or of an optical cable.

In a way, the optical fibre may be likened to the conductor of an electric communication cable. Indeed, it wouldn't be a bad idea at all to call it a light conductor – anyway, the name would be highly suggestive.

To repeat, numerous fibres or fibre bundles are combined into a communication cable. Sometimes it is called a fibre optical cable, sometimes a fibre cable or even an optical cable, perhaps by analogy with an electrical cable. In fact, the two have many things in common. Among other things, the fibres of an optical

cable can be wrapped around a metal strength member much as the conductors are twisted in an electric cable.

As with electric cables, optical cables have several thousand 'conductors', that is, optical fibres. It will be more accurate, though, to say that they might have. Most optical cables produced commercially and available on the market have as few as ten to fifteen fibres, although some makers turn out optical cables with as many as over a hundred fibres.

For further protection against mechanical injury and climatic vagaries, optical cables are encased in plastic, aluminium, steel, or composite outer sheaths. Some sort of armour may also be used, if and when necessary.

On the other hand, an optical cable has (or, at least, may have) some elements non-existent in an electrical cable, such as the primary coating to prevent abrasion and subsequent flaws in the material; the buffer coating (or jacket) which serves to protect the fibres against radial mechanical forces and (in some special designs) to provide enough room for the fibres to move relative to one another when the cable is being bent; and a conducting wire to feed power to the intermediate repeaters installed on the fibre-optic communications system.

In contrast to electric wire communications, multichannel fibre optic systems mostly operate on a time division multiplex (TDM) basis, using pulse-code modulation (PCM).

In them, the signal undergoes double conversion. The optical signal coming from the line is processed by a photodetector into an electric signal which is then amplified and restored to its original waveform. The regenerated electric signal is then converted to an optical signal again, and this is passed on along the line by a laser or a LED.

In optical multichannel systems, one fibreguide is used for transmission in one direction and another in the opposite direction, using the same frequency band. Thus, a two-fibre-guide optical circuit is equivalent to an electrically four-wire

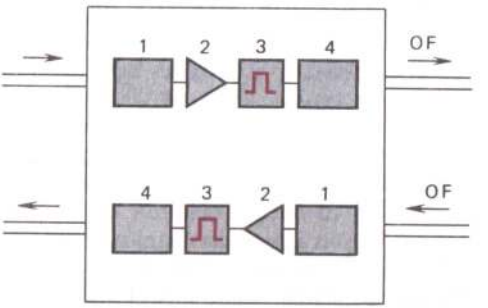


Fig. 9.7. Block diagram of a fibre optic line repeater: *1*, photodiode as optical-to-electric transducer; *2*, amplifier; *3*, regenerator; *4*, semiconductor laser as electric-to-optical transducer

carrier-frequency single-sideband circuit, and one fibreguide in such a case is equivalent to a physical pair of electric conductors. Of course, use may well be made of a single fibreguide for two-way transmission on a frequency division multiplex (FDM) basis.

When the idea to use optical fibres for communications was first put forward, the attenuation even in the best of cases was about a thousand decibels per kilometre. They would hardly have been able to do their job properly – this would have necessitated the installation of repeaters every thirty or forty metres. What was needed in order to translate the idea into practice were optical fibres with an attenuation of less than ten decibels per kilometre. This need was fulfilled before long.

In 1970, optical fibres were made with an attenuation of less than twenty decibels per kilometre. After ways and means had been found by 1975 to keep very low the concentration of the undesirable metals iron, copper, chromium, nickel and manganese and of the hydroxyl groups, high-silica glasses could be made with an attenuation of less than ten decibels per kilometre.

Table 20. Generations of Optical Fibre Cables

Generation	Years	Optical fibre type	Wavelength, μm	Attenuation, dB/km
First	1976-1980	Multimode:		
		step-index	0.85	10-20
		graded-index		5-8
Second	1981-1985	Multimode:		
		graded-	0.85	2.5-4
		index	1.3	1-2
Third	1986-1990	Single-mode	1.3	0.5-1

Indeed, the figure was lowered still more to under five decibels per kilometre by 1978, and the experimental glasses made in 1978 had an attenuation of as low as one decibel per kilometre – that was much better than one could hope for. This swept aside any doubts about optical cables and work began on experimental fibre optic communication facilities.

Although the history of fibre optic communications systems spans a mere decade, several generations of optical cables have been developed to date, differing not only in the fibre type used (step-index, graded-index, single-mode, and multimode), but also in the wavelength of light transmitted. As the wavelength goes up, the signal attenuation becomes progressively smaller.

As is seen from Table 20, the best third-generation optical fibres have an attenuation of as small as a half decibel per kilometre. Since the terminal amplifiers-regenerators can provide a gain of thirty to forty decibels, experimental lines from sixty to one hundred and twenty kilometres long can be installed with no intermediate repeaters at all. The losses of energy at splices are a mere 0.1 or 0.2 decibel per splice. By way of comparison, glasses for spectacles produce an attenuation of one or two thousand decibels per kilometre.

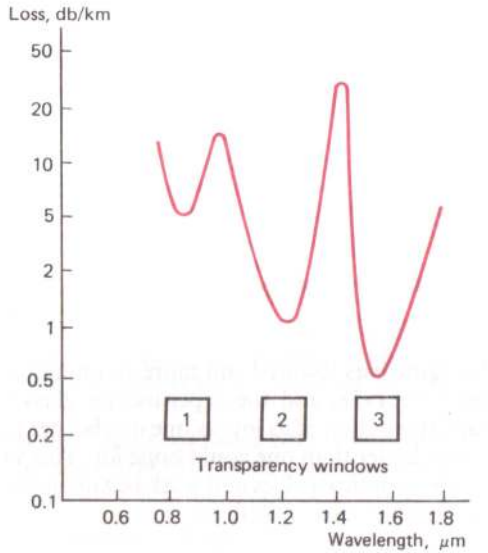


Fig. 9.8. Attenuation-vs-wavelength characteristic of a fused-quartz optical waveguide: *1-3*, 'transparency windows'

The signal reaching the end of an optical fibre communications system has not only to be amplified, but also restored to its previous shape, or regenerated. This explains why the terminal apparatus of such a system includes amplifiers-regenerators.

The manner in which the attenuation, α, varies with the wavelength, λ, of light is shown in the plot of Figure 9.8. As is seen, the attenuation is at its lowest at wavelengths of 0.85, 1.3, 1.55, and 2.6 micrometres – they mark what are known as 'transparency windows'. In real optical cables, the increase in wavelength from 0.85 to 1.3 micrometres causes the attenuation to fall to one-half or even one-quarter. In moving from

a wavelength of 0.85 to 1.55 micrometres, it falls to one-fifth or even one-tenth of its previous figure.

It must be realized, however, that the loss of energy suffered by the signal in a real cable is somewhat greater than is usually measured in 'pure form' on individual optical fibres. This increase is brought on during the various steps in optical cable manufacture: as the protective coatings are applied, the individual optical fibres are stranded into a cable, the other elements of the cable are added, and the entire assembly is encased in a sheath.

Four-fifths of the first-generation fibre optical communication links were shorter than ten kilometres, and only one-fifth were from ten to fifty kilometres long. Among the second generation, some already were several hundred kilometres long. Those in the third can span distances running into thousands of kilometres.

The field of fibre optic communications has been expanding at an impressive pace, indeed. While only twenty-three optical communication links were built between 1976 and 1978, their number increased to eighty-five between 1979 and 1981 – a growth of three and a half times. At this writing, several hundred fibre optic links are in operation.

Optical cables are mostly used in urban (or exchange) areas, with seventy per cent for interoffice connections, fifteen per cent in subscribers' loops, and the remaining fifteen per cent in toll (long-distance) trunks.

Optical cables hold special promise to cable television. Any community would usually have low houses located in the so-called 'shadow' zone for the reception of television programs, that is, where the taller buildings produce interference so that a poor-quality picture can only be seen on TV screens. One way out is to install an antenna on the tallest building in the area so that the incoming signals can be picked up good and clear, and to run optical cables to the lower buildings. The electric signal

emerging from the antenna goes through a converter and leaves it as an optical signal which is sent into the optical cable. On exit from the cable, the signal undergoes a reverse conversion, that is, from optical to electric, and is fed as such to a TV set.

In a desire to stress how slim optical fibres are, it is usual to compare them with a human hair. Sometimes one may even hear that 'an optical fibre is thinner than a human hair'. This is a suggestive simile, indeed – an optical fibre does look like a human hair, but it is thicker. The diameter of a human hair is twenty micrometres, and the more commonly used multimode graded-index optical fibres have, as recommended by the International Electrotechnical Commission (which is more commonly known by its French name: Commission Electrotechnique Internationale, abbreviated to CEI), a core diameter of 50 ± 3 micrometres and a cladding diameter of 125 ± 3 micrometres. As with coaxial pairs, it is customary to write the nominal dimensions of an optical fibre as a fraction, that is, 50/125. The primary coating is applied to an outside diameter of 250.

Step-index multimode optical fibres have larger dimensions, for example, 200/380 and 250/390. The nominal diameters of step-index single-mode optical fibres are 10/125, and the core may be from eight to twelve micrometres in diameter.

Silica and glass are not the only materials that are used for optical fibre manufacture. There are also optical fibres made of polymers, such as polystyrene and acrylic. Plastic optical fibres are easier to make than their silica and glass counterparts, and they have a better ability to withstand cyclic flexing. Unfortunately, they have higher attenuations (more than three hundred decibels per kilometre in the optical range), which makes them unsuitable for long-distance communications. On the other hand, plastic optical cables do well when used in short-distance hook-up cables, such as in computer applications.

Standing midway between glass or silica and plastic cables are

those which have a glass or a silica core and a polymer cladding. They usually come in sizes of 125/500 to 300/1100 micrometres.

Instead of glass, they may use an ultra-purified fused quartz core highly resistant to irradiation. The desired difference in refractive index (or the desired index profile) is obtained by using a polymer material for the cladding so that its permittivity is lower than that of the core. The attenuation of a fused quartz-plastic clad optical fibre is ten to twenty decibels per kilometre.

The near and the far. It is an unquestionable fact that optical cables are superior to electrical cables. Firstly, they have a larger traffic handling capacity because they can transmit a wider frequency spectrum. Secondly, they can transmit information at a far higher rate. Thirdly, they have lower attenuations (a 2.6/9.5 coaxial pair has $\alpha = 2.4$ to 4.8 decibels per kilometre at up to 4 megahertz, which rises to 55 decibels per kilometre at 500 megahertz), and this means that a greater spacing may be used between intermediate repeaters – they may be spaced ten to twenty kilometres apart in the case of multimode optical fibres and twenty-five to fifty kilometres in the case of single-mode fibres.

Armourless optical cables are remarkably small in diameter, ranging from three to thirty or forty millimetres, depending on the number of fibres stranded into a cable, and their weight is ten to nine hundred kilograms per kilometre. (By way of comparison, Soviet-made armourless lead-sheathed coaxial cables, such as KMG-4 and KMG-8/6, have an outside diameter of thirty to sixty millimetres, and their weight is three to six tons per kilometre.) Obviously, they are much easier to handle when laying in telephone ducts, and the ducts can be used to a better advantage.

Optical cables use very little, if any, copper. (Again by way of comparison, the Soviet-made KM-4 × 2.6/9.5 coaxial cable uses close on half a ton of copper per kilometre.) In a sense, we

are witnessing Professor Ayrton's prediction coming true – ever decreasing amounts of copper go to make cables. Still, cables themselves are not rejected.

Optical fibres are insensitive to the stray electromagnetic fields that may be set up by nearby power transmission lines, electro-traction railways, radio transmitters, and lightning discharges. Quite obviously, they need no electromagnetic shields to protect them. Nor do they radiate any electromagnetic waves of their own – in consequence, there is no mutual interference between them and, more importantly, complete security of communications is assured.

Last but not least, optical cables are extremely versatile. The same type of optical cable can be used in long-distance lines and in local networks to handle all types of communications: telephone, TV, and facsimile at the same time. Already in the early 1980s, the video information and data transmitted over fibre optic communications systems claimed a greater share than telephone messages. To believe forecasts, the fibre optic communications systems of the future will play a far greater role in the transmission of video information, including the videophone, cable television, and TV conference service. Fibre optic communications systems can readily be tailored to the psychological and physiological capabilities of human beings who receive information mainly by sight than by ear. The 'ear-brain' system can process fifty kilobits of information every second, while the 'eye-brain' system can handle as many as five megabits, or a hundred times more.

Increasingly more often we can read reports about 'wired houses' and 'wired cities'. What is meant are houses and cities incorporated into wide-flung communications networks which use optical cables to bring into the homes both the conventional telephone and the videophone, high-fidelity stereophonic broadcasts, high-speed data transmission, colour TV, and visual data displays.

The first example of 'wired cities' is Biarritz, a small seaside resort in the Bay of Biscay, France. It uses all kinds of optical cables: trunk, junction, and subscriber's loop, to provide the several thousand subscribers with telephone, videophone, TV, and other services.

Unfortunately, optical fibres and, therefore, optical cables are not strong mechanically. Although optical cables have about the same breaking strength as copper wire, they tend to develop microcracks. In the long run, microcracking may result in fibre breakage. Nor are optical fibres strong enough to resist compression from all sides. To this we should add microbending almost inevitably produced during cable manufacture, installation, and interconnection – it heavily adds to the cable attenuation. All of these factors are especially pronounced at low temperatures.

Several hundred configurations of optical communications cables have been developed and patented at this writing. They differ in the number of fibres stranded in a cable, the cable core structure, strength members, buffering, fillers, coatings, and sheathings. Optimal designs and production methods for optical cables have not yet been standardized. Still, there are several designs that seem to be predominant.

One uses a tight-buffered core stranded from individual optical fibres arranged in one or several layers, as shown in Figure 9.9. A single-layer cable (Figure 9.9*a*) has four plastic-coated fibres, *1*, and a strength member, *2*, which is a synthetic string of high strength. There are also expanded plastic buffer jackets, *3*, placed between the strength member and the fibres, on the one hand, and over the fibres, on the other. To prevent the fibres from moving round the periphery, they are held in place by large-sized plastic strings. Alternatively, this job may be done by conducting wires which serve as power-feeding elements, *4*. The cable core is encased in a polyethylene outer jacket or sheath, *5*.

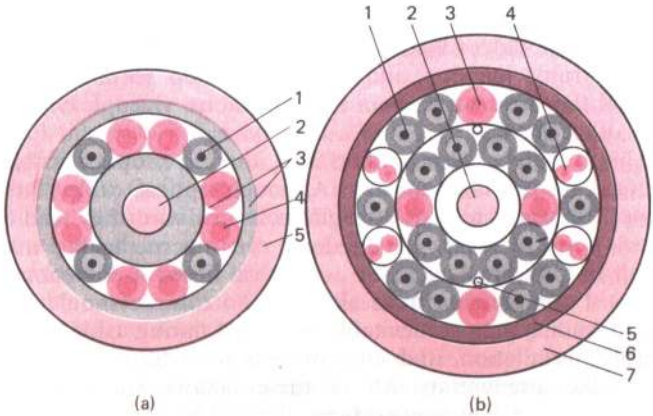


Fig. 9.9. Optical cable of layer construction: (*a*) single-layer and (*b*) double-layer

The two-layer cable shown in Figure 9.9*b*, as its name implies, has two layers of eighteen fibres, *1*, arranged around a central strength member, *2*, which is a plastic-coated steel wire. Disposed among the fibres are conducting wires, *3*, supervisory electric pairs, *4*, and testing wires, *5*. The cable core is encased in a polyethylene-laminated aluminium internal jacket, *6*, and an outer protective polyethylene sheath, *7*.

Another cable design is known as the unit type, that is, one stranded by the unit method. In this method, coated and buffered fibres (say, ten of them) are first stranded into minor groups, and the minor groups (say, five of them) are stranded together into major groups (each thus containing fifty fibres), and these are eventually made into the agglomerate bundle, or unit. In turn, the units are stranded in layers to make up a complete cable. It may be added that the fibres in each minor group are enclosed in what is called the filled loose buffer

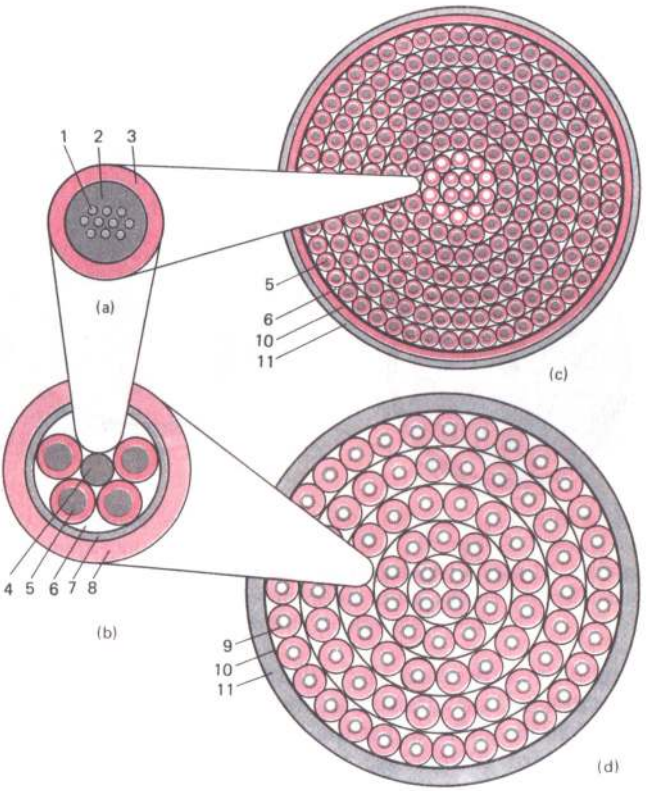


Fig. 9.10. Unit method of stranding: (*a*) minor group of ten fibres; (*b*) major group of fifty fibres; (*c*) cable stranded from minor groups with a total of two thousand fibres; (*d*) cable stranded from major groups totalling four thousand fibres; *1*, optical fibres; *2*, buffer-filling compound; *3*, minor group jacket; *4*, strength member; *5*, minor group; *6*, buffer-filling compound; *7*, unit belt insulation; *8*, unit jacket; *9*, major group or unit; *10*, cable core belt insulation; *11*, cable sheath

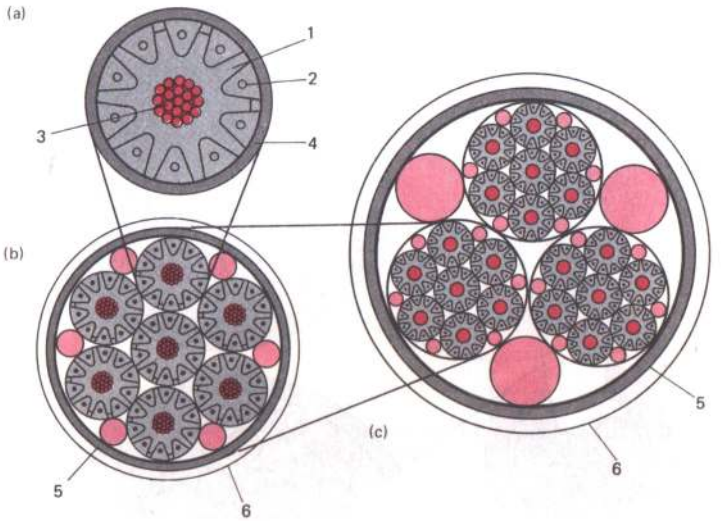


Fig. 9.11. Unit-type optical cable: (*a*) fibre unit consisting of ten optical fibres; (*b*) optical cable consisting of 70 optical fibres; (*c*) optical cable consisting of 210 optical fibres

jacket, and so they may be called 'loosely-buffered'. In some cable designs, the individual fibres may be enclosed in an unfilled loose buffer jacket.

In a third design, use is made of an extruded plastic structural member (shown at *1* in Figure 9.11), and the individual fibres, *2*, are placed in the slots made on the surface of this member. Passing through its centre is a strength member, *3*, and there is an outer plastic covering or tubular jacket, *4*, surrounding the unit thus obtained. Indeed, many makers class this design among the unit type cables.

The cable core may consist of one or several (say, seven)

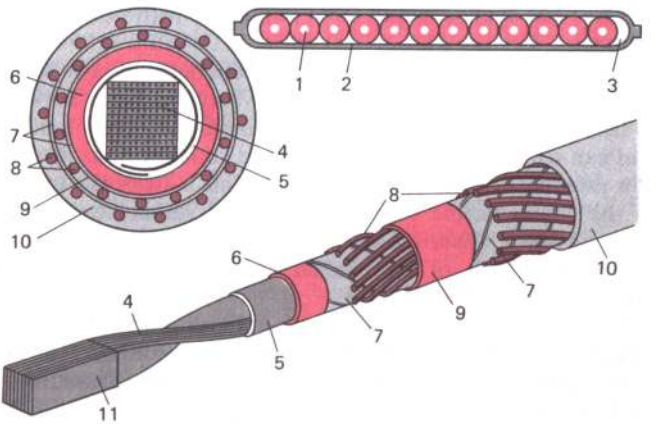


Fig. 9.12. Ribbon optical cable: *1*, optical fibres; *2*, polyester tape; *3*, filling compound; *4*, cable core: $12 \times 12 = 144$ optical fibres; *5*, belt insulation; *6*, inner polyethylene jacket; *7*, polyester tape; *8*, strength members; *9*, intermediate polyethylene jacket; *10*, outer protective polyethylene jacket or sheath; *11*, connector

units. The cable core is protected by an aluminium inner sheath, *5*, and an outer polyethylene jacket, *6*. The seven-unit cable has seventy fibres, and the multi-unit cable has two hundred and ten fibres.

In a fourth design the cable core is square or rectangular and not round in cross-section as in all other cable types. This is the ribbon type of optical cable. Here the core is assembled from ribbons each of which may contain several fibres. The ribbons are stacked one upon another and then twisted in a spiral for better flexibility. Most often, such a cable will use twelve rows of twelve ribbons each, as shown in Figure 9.12.

The cable core may have two or three protective polyethylene jackets, with one or two of them reinforced with power feeding elements.

This type of cable, with an outside diameter of only slightly less than thirteen millimetres, is laid between New York and Washington, a distance of three hundred and fifty kilometres, and can carry 240 thousand telephone conversations at a time at a rate of 274 megabits per second. This is twice the capacity of the coaxial cable used in the 10 800-channel carrier telephony system. Also, the diameter of the optical cable is just one-sixth of that of the coaxial cable (which is seventy-six millimetres, or three inches).

So far we have been dealing with underground optical cables installed in ducts or directly buried in ground. However, optical cables may well be used for underwater installation as well. In the early 1980s the best transoceanic coaxial cables fifty millimetres in diameter could carry four thousand telephone conversations at a time in the frequency band up to thirty megahertz. With the repeaters spaced nine and a half kilometres apart, the overall transmission distance was seventy-four hundred kilometres, and this meant that a total of nearly eight hundred transistor repeaters were needed for proper operation of the line. By that time the underwater carrier telephony lines had had behind them a quarter of a century of development, during which the size of coaxials had trebled, the cable design had been highly improved, the vacuum-tube repeaters had given way to transistor repeaters, and the remotely fed supply voltage had been raised three and a half times. With all of these advances, fifteen times as many repeaters could now be inserted in a line and the frequency spectrum transmitted had been increased two hundred times.

However, a further increase in the capacity of coaxial cable lines to, say, ten thousand channels would call for an increase

in cable diameter to sixty millimetres and the repeater spacing would have to be reduced to four kilometres. All this would add to the complexity of cable laying, repeater power feeding, and circuit maintenance. The time has thus come when the rapidly growing demand for a greater transmission capacity can no longer be satisfied by simply expanding the traditional facilities.

Symptomatically, TAT-7 installed between the USA and Britain in 1983 and TAT-6 laid between France and the USA in 1976 can only carry four thousand telephone channels each. The figure doesn't look impressive at all if we recall that telephone traffic across the Atlantic doubles on average every four years.

The promise of a fundamentally new qualitative jump in submarine cable communication is held by optical cables. The first attempts to lay short links – from ten to a hundred kilometres – at depths from a hundred metres to seven kilometres were made in the early 1980s. In the mid-1980s several commercial optical communication links went into operation: the 120-kilometre optical cable between Tenerife and Gran Canary in the Canary Islands, the 122-kilometre link between Broadstairs, England and Ostend, Belgium, and the 420-kilometre link between Marseille, France and Ajaccio, Corsica. The latter half of the 1980s saw the construction of two first transoceanic optic communication systems, one across the Atlantic and the other across the Pacific. The Atlantic cable, or TAT-8, has linked the USA to both England and France. The Pacific cable has joined the USA via Hawaii and Guam to Japan.

The two unit designs most commonly used in submarine optical cables are shown in Figure 9.14. In unit *a*, the optical fibres, *1*, are enclosed in what is called the tight buffer, *2*. In unit *b*, use is made of an extruded plastic structural member, *2*,

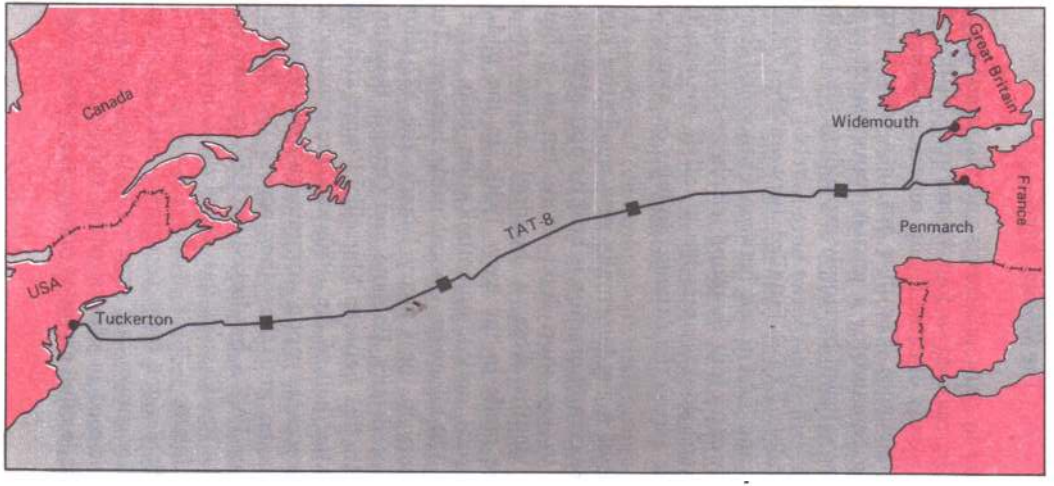


Fig. 9.13. The route of TAT-8, the first Atlantic optical cable linking the USA to Britain and Europe

with helically arranged grooves or channels, and these receive loosely fitting optical fibres. In each of the above designs, there is a central strength member in the form of a steel wire, *3*. The entire assembly is enclosed in a Nylon jacket, *4*. The free spaces in the loose structural member in unit *b* are filled with a water-resistant compound, *5*.

If we look at Figure 9.14*c*, we can see that the core, *6*, of the optical cable is surrounded by a layer or two of high-strength steel wire, *7*, which acts as a strength member. On top of it is a welded copper or aluminium tube, *8*, which acts as a barrier keeping seawater out of the cable and doubles as a conductor feeding power to repeaters (the return conductor of the power-feeding circuit is seawater). The entire assembly is enclosed in a polyethylene sheath, *9*. It insulates the welded tube, *8*, from contact with seawater. The outside diameter of this cable is twenty to twenty-two millimetres.

Advances in fibre optic communications have reached a point where we may well start an independent inventory of optical cable generations. The 'vital statistics' of the first generation may be summed up as follows.

Optical fibres per cable	six
Optical fibre type	single-mode
Carrier wavelength	1.3 micrometres
Fibre pair capacity	2 × 1920 telephone channels
Repeater spacing	40-55 kilometres
Cable attenuation	0.5 decibel/kilometre
Nominal transmission rate	280 megabits/second

Incidentally the same amount of data can be handled by a twin quaternary digital transmission system, the transmission rate for each line being 140 megabits per second.

The lowest attenuation that can be achieved with ultra-purified fused-quartz optical fibres is, probably, 0.1 decibel per kilometre. This means that in the long run the repeater spacing

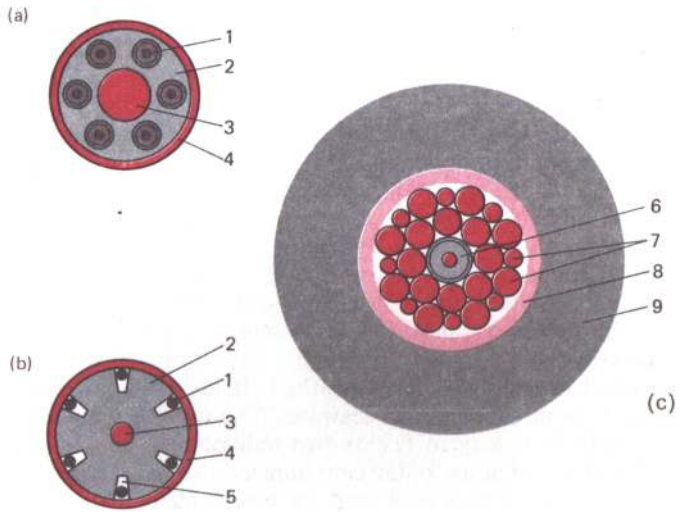


Fig. 9.14. Submarine optical cable

may be extended to three or four hundred kilometres. This seems to be the limit for fused-quartz fibres, but chances are that towards the end of the century new ultra-purified materials will have been developed, such as fluorine glasses doped with zirconium or hafnium and causing still lower radiation losses. The promise of a substantial decrease in optical cable attenuation is also held by operation at the longer wavelength of infra-red radiation: first, at two to three micrometres, then at three to six micrometres and at six to twelve micrometres in the future. There is ground for hoping that the overall losses in an optical cable line, including splice losses, will be reduced to 0.015 decibel per kilometre. It may so happen that an ideal transoceanic telephone line will eventually be built with as few as one or two repeaters or no

repeaters at all – a thing that appears fantastic today. But we ought not to forget that fibre optic communications are advancing at a truly neck-breaking pace and may well exceed any expectations, however optimistic they may sound.

The 1980s saw the infancy and childhood of optical communication cables. The 1990s will surely witness their coming of age on all lines – between telephone exchanges, between cities, and on international long-distance trunks.

WILL THERE BE CABLES IN THE YEAR 2000?

Quite a number of tags have been stuck to the twentieth century. One, attributed to Norbert Wiener, the father of cybernetics, names it as the age of communications and control. Communications today is developing extremely rapidly even by the standards of our high-speed century. Modern forms of communications include the telephone and the videophone, telegraph and facsimile, data transmission, radio broadcasting and telecasting. Of course, telephone communication is prevalent.

The pace at which telephony has spread over the face of the globe cannot be named other than sky-rocketing. It took eighty years (from 1876 to 1956) to install the first hundred million telephone sets, and a mere ten years (from 1956 to 1966) to install the second. The third was installed in a matter of six years, the fourth in four and a half years, the fifth in four years, and the sixth in three years. In the twentieth century, the globe's population doubles approximately every forty years, and the number of telephones every ten to eleven years. In the latter half of the twentieth century the world's population has been growing at a rate of about two per cent (in recent years, the rate of growth has fallen to 1.7 or even 1.6 per cent), and the number of telephones has been increasing at an average rate of six per cent.

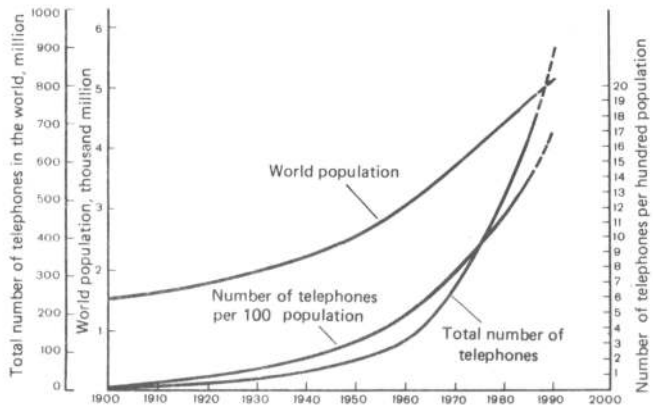


Fig. 9.15. Telephone services of the world

Statisticians know how the Earth's population increases every hour, minute and even second. During any twenty-four hours, 220 thousand are added to the total. The number of telephones installed at our homes, in offices and elsewhere goes up by a hundred thousand during the same span of time.

It takes close on two years to gather and process global statistical data. With an accuracy sufficient for our purpose, it may be assumed that by 1989 the world's population will be 5.2 thousand million, and the number of telephones in use will be 800 million. Thus, there will be just over fifteen telephones per hundred population.

To believe demographers, the world's population in the year 2000 will be 6.1 or 6.2 thousand million. Assuming that the annual increase in the number of telephones is six per cent, it is an easy matter to find (as one finds the compound interest on one's capital) that the world will have 1.5 or 1.6 thousand million telephones by that time. This means that as many

telephones will be installed in the next ten years as were over the previous one hundred and fifteen years, and there will be twenty five telephones per hundred population.

However, the number of telephones in use is not the only yardstick with which to measure the demand for communication channels. The pace of growth is still more impressive in the telephone traffic carried, that is, the amount of information exchanged by telephone. In recent years, the rate of expansion of telephone traffic has levelled off at ten per cent per year.

In 1885, or a little more than a century ago, a total of about four hundred million telephone calls were made. Nowadays, the number of telephone calls made the world over is close to a thousand thousand million a year. In Europe, the average figure per telephone in use is 1500 to 1600 calls a year. In Sweden, Mexico and France the figure reaches 4500 to 6500, and in the United States and Canada it is about 2500.

Of the total number of telephone calls, from eighty-five to ninety per cent are made over local (urban and rural) networks, and some ten per cent over long-distance (toll) lines.

The revenue from the telephone service accounts for nearly eighty per cent of the money paid for all types of electric communications and increases fourfold to fivefold every decade. It is not without a reason that sociologists note ironically that people have lost the habit of writing letters to one another – they prefer to communicate by telephone.

It is instructive to compare the growth of telegraph and telephone traffic. In Great Britain, a country with highly advanced communications facilities, a total of forty million telegrams were sent and a total of fourteen hundred million telephone calls were made in 1931. In 1981, the British paid for twenty thousand million telephone calls – a fourteen-fold increase. In the meantime, the number of telegrams had fallen to three million which is one thirteenth of the previous figure.

According to the Moscow Post Office, every Muscovite receives an average of ninety to a hundred letters and four or five telegrams every year, which is a few tenths or even a few hundredths of the average number of telephone calls, which is about three thousand per inhabitant per year.

A matter of an ever-growing importance to society is the problem of data transmission and reliable communication among high-speed computer complexes. The Soviet Union has a total of over three hundred computerized management information systems in the various industries, and plans are afoot to set up a nation-wide computer network that will do all accounting, planning and management for the entire national economy. The network will offer a means for a timely use of information in all fields of man's activity – production, commerce, everyday life, education, environmental control, and culture.

The 'information explosion' that we are witnessing nowadays makes it a necessity to provide adequate plant and a huge number of channels for the transmission of information. Incidentally, over sixty per cent of the computers in service in the United States are oriented to operate in partnership with communications systems.

Various types of communications are used for the purpose: cables, radio-relay links, satellites, tropospheric scatter, the ionosphere and meteor bursts. In the USSR, they have been merged into a single automated communications network set up as a combination of switching centres and radial links. It combines all local (that is, urban and rural) areas, zones (into which all of Soviet territory is divided), and long-distance trunk lines.

Although wire and radio communications are what may be called the antipodes (at least, as far as the medium used for transmission is concerned), they complement each other and cooperate within the world's communications system where

each does a job best suited for it. If we borrow an expression from Soviet sports news, they are friendly rivals, both contributing to the progress of mankind.

Still, cable lines have a greater share in both the national and the world communications networks. Radio communications are liable to blackouts and cannot therefore guarantee absolute reliability. Communications over what are known as open-wire lines depend on many atmospheric factors, such as pressure, temperature, solar flares, thunderstorms, magnetic storms, and even time of day and season of the year. On their part, cable lines offer reliability, security, protection against atmospheric factors and mutual interference, and high fidelity, which is especially important in data transmission to computers.

In the view of what we have said, only one answer may be given to the question we asked a bit earlier: Yes, cables will remain in service in the year 2000 and, indeed, in the twenty-first century.

What sort of cables will they be? Of course, both electric and optical. It would be naive to think that everything in the twenty-first century will 'go optical' at once, as if by magic. It is not at all simple to replace the factories that are now turning out millions of kilometres of electric communication cable, to install new plants, to provide facilities preparing high-quality low-loss optical fibres, to develop suitable optical cable designs and, especially, to acquire the know-how necessary for the manufacture of optical cables. All this will take a lot of time to do.

In short, much as the twentieth century may be named the century of electric cables, so the twenty-first century may be called the century of electric and optical cables with an ever increasing share taken up by the latter. But still it will be a century of cables.

Cables which will give any user access to the telephone and

videophone, radio and telecasts free from any interference, motion pictures of his own choice, copies of newspapers, magazines and books from libraries, data banks, and computers.

Cables which, backed up by lasers and computers, will revolutionize data transmission and communications in general.

Cables which will make up a still wider cobweb all over the face of our planet, dwarfing the net of underground and underwater cables at work today.

Cables which will give users reliable links in every village or city, between cities, from country to country, and from continent to continent – all over the globe.

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Glossary

AERIAL CABLE – A cable installed on a pole line or similar overhead structure.

ALPETH – A type of cable sheath consisting of an aluminium shield and a polyethylene jacket.

AMERICAN MORSE CODE – A system of dot-and-dash signals originated by Samuel F. B. Morse and still used to a limited extent for wire telegraphy in North America. It differs from the International Morse code used in radiotelegraphy.

AMPLIFIER – A device which draws power from a source other than the input signal and produces as an output an enlarged reproduction of the input.

ARMOUR – A protective covering of jute, steel tapes or wires over the sheath of a telephone cable to prevent damage during its service life.

ATTENUATION – The decrease in the amplitude of a signal during its transmission from one point to another. It may be expressed as a ratio or in decibels.

AUDIO – Pertaining to frequencies which correspond to a normally audible sound wave. These frequencies range roughly from 15 to 20 000 hertz.

AUDION – The three-electrode vacuum tube invented by Lee de Forest.

AUTOMATIC TELEPHONE EXCHANGE – A telephone exchange in which connections are made between subscribers without the intervention of an operator.

BALANCED LINE – A line using two identical conductors operated so that they are electrically alike and symmetrical to a common reference point.

BANDPASS FILTER – A wave filter with a single transmission band. It attenuates frequencies on either side of this band.

BAND-STOP FILTER – A wave filter with a single attenuation band. It passes frequencies on either side of this band.

BEADED COAX – A coaxial cable in which the dielectric consists of beads made of various materials.

BEL – The fundamental unit on a logarithmic scale for expressing the ratio of two powers. The number of bels is equal to $\log_{10}(P_1/P_2)$.

BIT – Abbreviation for 'binary digit'. A unit of information equal to one of two possible states (such as 1 or 0).

BRAID – A weave of organic or inorganic fibre used as a covering for a conductor or group of conductors. A woven metal tube used as a shielding around a conductor or group of conductors.

BUFFER COATING – It is applied to a primary coated optical fibre to provide protection against external mechanical and environmental influences. Also called the secondary coating or jacket.

BURIED CABLE – A cable that is buried directly in the ground without being placed in an underground conduit.

CABLE – An assembly of one or more conductors usually within a protective sheath and so arranged that the conductors can be used separately or in groups.

CABLE CORE – That portion of an insulated cable lying under the protective covering or jacket.

CABLE FILLER – Material used in multiple-conductor cables to occupy the spaces between the insulated conductors.

CABLE MORSE CODE – A three-element code used mainly in submarine cable telegraphy.

CABLE REEL – A large wooden or steel spool on which cable is wound for shipping and storage. Also called 'cable drum'.

CABLE SHEATH – The protective outer covering of the cable core. For many years it was a lead alloy. At present, it is usually composite, using layers of copper, aluminium, or steel in various combinations.

CABLE SHIELD – The metallic components of a cable sheath that act to prevent outside electrical interference and to drain off current induced by lightning discharges.

CALL – The action performed by the calling party or the operations necessary in making a call or the effective use of a connection between two subscribers.

CARRIER – A wave of constant amplitude, frequency and phase, which can be modulated by changing any one of these.

CARRIER-CURRENT COMMUNICATION – The superimposition of a high-frequency current on ordinary telephone or telegraph frequencies for telephone communication.

CARRIER SYSTEM – A means of obtaining a number of channels

(multichannel operation) over a single path by modulating each channel upon a different carrier frequency and demodulating at the receiving end to restore the signals to their original form.

CARRIER TELEPHONY – That form of telephony in which carrier transmission is used, the modulating wave being at an audio frequency.

CENTRAL OFFICE – A building housing telephone switching apparatus.

CHANNEL – (1) A portion of the frequency spectrum. (2) A single path for transmitting electric signals.

CHANNEL CAPACITY – The maximum possible information rate through a channel, such as bits per second.

CLADDING – The transparent material surrounding the fibre core of an optical fibre and having a slightly lower refractive index. It supports the core and reduces the radiation loss into the surrounding air.

COAXIAL CABLE – Also called coaxial line, concentric line, or simply a coax. In it, one conductor completely surrounds the other, the two being coaxial and separated by a continuous solid dielectric or by dielectric spacers. Such a line has no external field and is not susceptible to external fields from other sources.

COHERENT LIGHT – Light at a single frequency, with all of its wave trains in phase.

COIL LOADING – The insertion of coils into a line at uniformly spaced intervals.

COMMUNICATION LINK – The physical means of connecting one location to another for the purpose of transmitting and receiving information.

COMPOSITE CABLE – A cable in which conductors of different types (such as pairs and coax) are combined under one sheath.

CONCENTRIC-LAY(ER) CABLE – A cable composed of a central core surrounded by one or more layers of helically laid conductors.

CONCENTRIC STRANDING – A method of stranding conductors in which the final conductor is built up in layers such that the inner diameter of a succeeding layer equals the outer diameter of the underlying layer.

CONDUCTOR – A bare or insulated wire or combination of wires not insulated from one another, suitable for carrying electric current.

CONDUIT – A raceway for holding wires or cables.

CORD – One or a group of flexible insulated conductors covered by a flexible insulation and equipped with terminals.

CORE – The transparent material of an optical fibre, surrounded by a transparent cladding of a slightly lower refractive index.
CROSS-TALK – Interference which appears in a given transmission channel but has its origin in another channel.
CUPETH – A cable sheath similar to ALPETH except that copper is used as the shield, instead of aluminium.

DECIBEL – Abbreviated dB. The standard unit of transmission gain or loss and relative power levels. One decibel is one-tenth of a bel.
DELAY – The time required for a signal to pass through a device or a line.
DEMODULATOR – A device which operates on a carrier wave so as to recover the wave with which the carrier was originally modulated.
DIAL TONE – A hum or other tone employed in a dial telephone system to indicate that the line is not busy and that the equipment is ready for dialling.
DIAPHRAGM – A flexible membrane used in electroacoustic transducers for producing audio-frequency vibrations when actuated by electric pulses, or electric pulses when actuated by audio-frequency vibrations.
DIELECTRIC – Any material used in a cable that will insulate one conductor from another or from a shield.
DIELECTRIC STRENGTH – The maximum voltage that a dielectric can withstand without rupturing. Also called 'electric strength', 'breakdown strength'.
DIODE – A two-terminal device which will conduct electricity more easily in one direction than in the other.
DISTRIBUTION CABLE – A cable used for distribution to subscribers.
DROP WIRE – One or more pairs of insulated wires used to run a subscriber's line from the distribution terminal at a pole to the protector on the subscriber's premises.
DUCT – Conduit for the installation and protection of cable in congested areas.

ELECTROLYTE – A substance in which the conduction of electricity is accompanied by chemical action.
ELECTROMAGNET – A temporary magnet consisting of a solenoid and an iron core. A magnetic field exists only while current flows through the solenoid.

EXCHANGE-AREA CABLE – Cable used to provide service in the local area around an exchange.

FEEDER CABLE – A communication cable extending from a central office (telephone exchange) along a primary route (main feeder cable) or from a main feeder cable along a secondary route (branch feeder cable) and providing connections to one or more distribution cables.

FIBRE-OPTIC BUNDLE – An assembly of optical fibres.

FILLER – A nonconducting component cabled with insulated conductors to impart roundness, flexibility, tensile strength or a combination of all three to the cable.

FILTER – Also called 'electric wave filter' or 'electric filter'. A device that separates electric waves differing in frequency.

FREQUENCY TRANSLATION – The transfer, en bloc, of signals occupying a definite frequency band, such as a channel or a group of channels, from one position in the frequency spectrum to another.

FUNDAMENTAL FREQUENCY – Also called 'the fundamental', the principal component of a wave, that is, the component with the lowest frequency or the greatest amplitude.

GAIN – Any increase in power when a signal is transmitted from one point to another.

GALVANIC – An early term for current resulting from chemical action, as distinguished from electrostatic action.

GALVANIZING – The coating of steel with zinc to retard corrosion.

GROUND – (1) A metallic connection with the earth to establish ground potential. (2) The voltage reference point in a circuit.

GROUND-RETURN CIRCUIT – A circuit which has a conductor (or two or more in parallel) between two points and which is completed through ground or the earth.

GUTTA-PERCHA – A natural vegetable gum, similar to rubber, used in the past mainly as insulation for submarine cables.

HANDSET – A telephone-type receiver and transmitter mounted together.

HARMONIC – A sine wave having a frequency that is an integral multiple of the fundamental frequency. For example, a wave with

twice the frequency of the fundamental is called the second harmonic.

HIGH-PASS FILTER - A filter having a single transmission band extending from some critical, or cutoff, frequency other than zero, up to infinite frequency.

IMPREGNATED - Permeated with a suitable protective material to keep out moisture, etc.

INSULATED - Separated from other conducting surfaces by a non-conducting material which presents a high, permanent resistance to the passage of current.

INSULATION - A non-conducting material that prevents the leakage of electricity from a conductor, provides mechanical spacing or support, and protects against accidental contact.

INTEREXCHANGE LINE - A line connecting two different exchange areas.

INTERFERENCE - Any electrical or electromagnetic disturbance, man-made or natural, which causes, or can cause, undesirable response.

INTERMEDIATE REPEATER - A repeater used other than at the end of a line.

INTERNATIONAL MORSE CODE - Also called Continental code. It differs from American Morse code in some code combinations.

ISOMER - One or two or more substances composed of molecules having the same kinds of atoms in the same proportions but arranged differently. Hence, the physical and chemical properties are different.

JACKET - A covering over a cable. It is usually the outer component of a composite sheath.

JUTE - Cordage fibre (such as hemp) saturated with tar and used as a protective layer over cable.

JUTE-PROTECTED CABLE - A cable having its sheath covered by a wrapping of tarred jute.

LANDLINE - A telegraph or telephone line passing over land, as opposed to submarine cables.

LAP WRAP - Tape wrapped around the cable core in an overlapping manner.

LASER – A device transforming incoherent light (light at various frequencies) into a very narrow, intense beam of coherent light. The acronym for Light Amplification by Stimulated Emission of Radiation.

LAY – The axial distance required for one cable conductor or conductor strand to complete one revolution about the axis around which it is cabled.

LEAD-COVERED CABLE – A cable with a lead sheath which offers protection from the weather and mechanical damage.

LEYDEN JAR – The original capacitor. It consists of metal foil on the inside and outside of a glass jar. The foil serves as the plates and the glass as the dielectric of the capacitor.

LOADING COIL – A coil of wire wound around a magnetic core, which provides a lumped impedance that can be inserted in series with a cable pair to improve voice frequency transmission.

LOADING SECTION – The length of cable between two load points.

LOW-PASS FILTER – A filter which passes all frequencies below a specified frequency with little or no attenuation but blocks the passage of the higher frequencies.

MAGNETIC NEEDLE – The magnetized needle such as used in a compass. When freely suspended, it will point to the Earth's magnetic north and south poles.

MIRROR GALVANOMETER – A suspended coil instrument which, instead of using a pointer to indicate the reading, employs a light beam reflected from a mirror attached to the moving coil.

MODULATOR – A device which modifies some characteristic of a wave (called the carrier) so that it varies in step with the instantaneous value of another wave (called the modulating wave or signal).

MULTIPLE-TWIN QUAD – Quad cable in which the four conductors are arranged in two twisted pairs, and the two pairs are twisted together.

NEPER – Also called napier. The fundamental division of a scale for expressing the ratio between two currents, powers, or voltages. One neper equals 0.8686 bels or 8.686 decibels.

NOISE – Any unwanted signal picked up on a cable circuit that is unintelligible.

OIL-FILLED CABLE–A cable having insulation impregnated with an oil which remains fluid at all operating temperatures, and provided with facilities to maintain a positive oil pressure within the cable at all times.

OPEN WIRE–A conductor separately supported above the earth's surface.

OPTICAL FIBRE–A structure consisting of a transparent (glass) core (see CORE) and an outer cladding (see CLADDING), the two differing in refractive index so that the light beam is confined within the fibre.

OPTICAL FIBRE BUNDLE–An assemblage of many optical fibres, primarily intended to avoid the breakage problem of single fibre links. With numerous fibres bundled together, if a few should break, many will still be left to carry the signal.

PAIR–Two wires forming a single circuit, held together by twisting, binding, or a common jacket.

PAPER-INSULATED CABLE–Cable in which the conductors are insulated with a paper ribbon either spirally or longitudinally applied.

PHANTOM CIRCUIT–A superimposed circuit derived from two suitably arranged pairs of wires called side circuits. Each pair of wires is a circuit itself and, at the same time, acts as one conductor of the phantom circuit.

PLASTIC-INSULATED CABLE (PIC)–Cable in which the conductors are insulated with plastics, such as polyethylene and polypropylene. Note: PVC-insulated conductors are not referred to as PIC.

POWER CABLE–A cable used to convey electric power from one location to another.

PRIMARY COATING–The coating given to an optical fibre during manufacture in order to prevent abrasion of the glass-core surface and subsequent flaws in the material.

PRINTING TELEGRAPHY–Telegraphy operation in which the received signals are automatically recorded as printed characters.

PULP-INSULATED CABLE– Cable in which the individual conductors are insulated directly with paper pulp (water-pulp slurry).

PUPIN COIL–An iron-core loading coil inserted into telephone lines at regular intervals to balance out the effect of capacitance between the lines.

QUAD A structural unit employed in cables. A quad consists of four separately insulated conductors twisted together.
QUADDED CABLE – A cable in which some or all of the conductors are in the form of quads.

REED – A thin bar located in a narrow gap and made to vibrate mechanically, electrically, or magnetically.
REGENERATIVE REPEATER – A repeater that restores signals to their original shape.
REPEATER – Also called a one-way or a two-way repeater. A combination of apparatus for receiving signals from either one or both directions, respectively, and delivering corresponding signals which have been amplified or reshaped or both.
RIBBON OPTICAL CABLE – An optical cable in which the individual fibres are arranged in a flat ribbon sandwiched between plastic tapes.

SECONDARY COATING – Also called 'buffer coating' or 'jacket'. It is applied to a primary coated optical fibre to provide protection against external mechanical and environmental influences.
SERVING – Of a cable, a wrapping applied around the core before it is lead-covered, or over the lead if the cable is armoured. Some common serving materials are jute, cotton, or duck tape.
SHEATH – A protective covering made of metals or plastics over the cable core.
SHIELDED CABLE – A cable surrounded by a separate conductor called the shield, intended to minimize the effects of adjacent electrical circuits.
SINGLE-WIRE LINE – A transmission line that uses the ground (or seawater) as one side of the circuit.
SOUND PRESSURE – The instantaneous pressure minus the static pressure at some point in a medium when a sound wave is present.
STALPETH – A type of cable sheath having a corrugated aluminium tape over the core, then a corrugated steel tape soldered at the overlap, a flooding of protective compound, and a polyethylene jacket overall.
STRAND – One of the wires or groups of wires of any stranded conductor.
STRANDED CONDUCTOR – A conductor composed of a group of wires usually twisted or braided together.
STRANDING – The manufacturing process by which pairs or other transmission circuits are orderly formed together to make a cable

core or unit. Usually, stranding imparts a long spiral lay which gives flexibility to the cable.

STRENGTH MEMBER – The central (most often, steel) wire of an optical cable, which acts as the primary load-bearing element.

STRUCTURAL MEMBER – The member of an optical cable, usually included to serve as a core foundation around which the buffered fibres may be wrapped or into which they may be slotted.

SUBMARINE CABLE – A cable designed for service undersea.

TELEPHONE REPEATER – An assemblage of amplifiers and other equipment employed at points along the line to rebuild the signal strength in a telephone circuit.

TELEPHONE TRANSMITTER – A microphone used in a telephone system.

TERMINAL REPEATER – An assemblage of equipment designed specifically for use at the end of a communication line, as contrasted with the repeater designed for an intermediate point.

TRUNK – A telephone line or channel between two central offices (telephone exchanges).

TWISTED PAIR – A cable composed of two small insulated conductors twisted together without a common covering.

UNBALANCED LINE – A transmission line in which the voltages on the two conductors are not equal with respect to ground (one example is a coaxial line).

UNDERGROUND CABLE – A cable installed below the surface of the earth in conduit or ducts. Does not include cables buried directly in the ground.

UNIT-TYPE CABLE – A cable in which the pairs are first formed into bound units and then the units are formed together to make the completed cable.

VOLTA EFFECT – The difference of potential that exists when two dissimilar, uncharged metals are placed in contact. One becomes positively charged and the other negatively, the amount of potential depending on the nature of the metals.

VOLTAIC PILE – A voltage source consisting of alternate pairs of dissimilar metal discs separated by moistened pads, forming a number of elementary primary cells in series.

VOLTA'S LAW – When two dissimilar conductors are placed in contact, the same contact potential is developed between them, whether the contact is direct or through one or more intermediate conductors.

WATER BARRIER – In a cable, the material, usually in the form of an axially laid aluminium foil/polyethylene laminated film, placed immediately inside the sheath. As an alternative, this may be a moisture-resistant material filling the spaces in the cable.

WAVELENGTH – In a periodic wave, the distance between points of corresponding phase of two consecutive cycles.

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To the Reader

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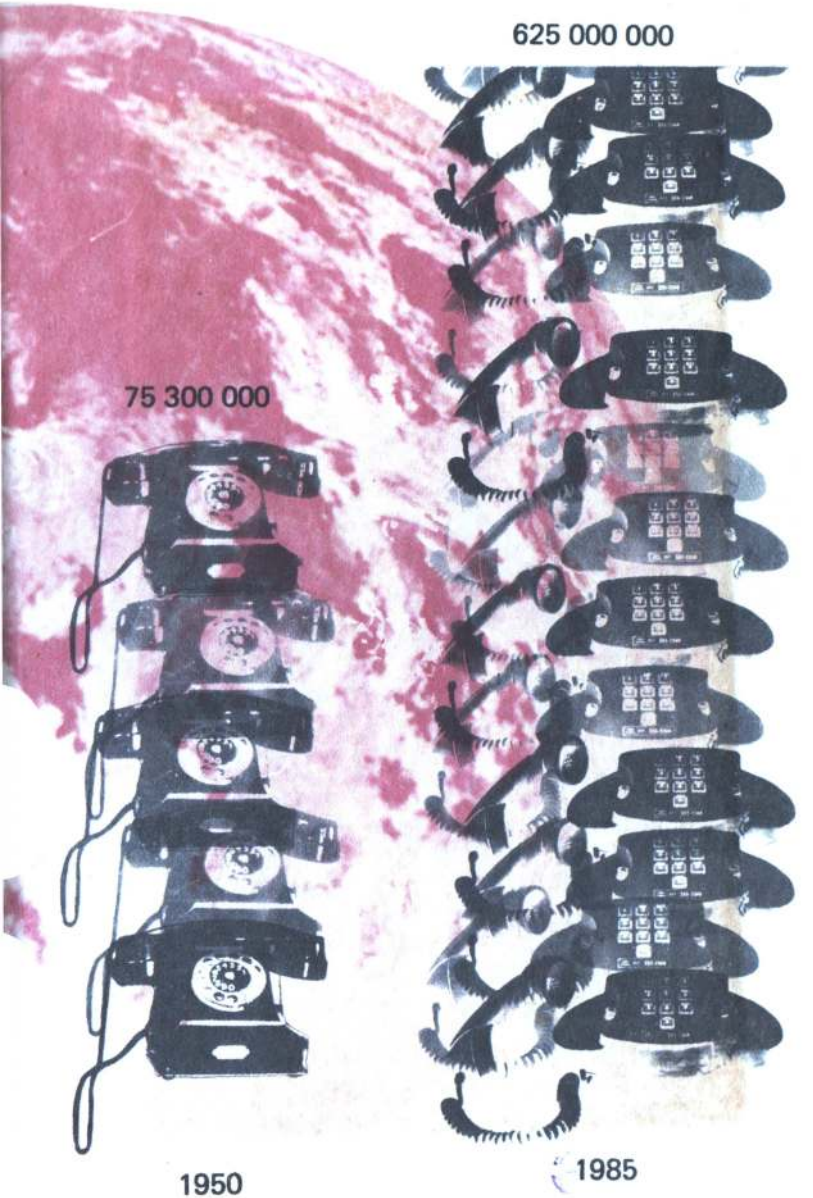
NUMBER OF TELEPHONE SETS
IN THE WORLD BY YEARS

480 000

1890

20 800 000

1920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75 300 000
1950
1985